Final Report
IPRO 326 – Spring 2005
Hybrid Electric Vehicles: Simulation, Design, and Implementation

Objective

The objective of IPRO 326 is to simulate various hybridization methods on three different types of vehicles. The members of the IPRO will focus on two different hybridization configurations, Parallel and Series; they will also focus on two methods within each of these configurations. The plans include converting a HUMMER H3, a HMMWV (High-Mobility Multipurpose Wheeled Vehicle), and a Passenger Bus to Hybrid Electric Vehicles (HEV). In order to accomplish these goals, the team will review results from previous semesters and attempt to optimize the performance of the vehicles. Conclusions will be based purely on simulation results obtained from the ADVISOR software that will be used throughout the semester. The intention of the IPRO is to propose a viable hybridization method that could be implemented by any interested auto manufacturers.

Background

The concept of More Electric Vehicles (MEV) emphasizes the use of electrical systems over the conventional mechanical, hydraulic, and pneumatic systems. This emphasis on electrical systems stems from the desire to improve performance, fuel economy, security and reliability. The appeal of fuel economy, and fuel economical vehicles is most prevalent as crude oil prices exceed record highs. The most practical solution for the Automotive Industry to realize the goals of high fuel economy as well as low emissions, is through the advancement and implementation of Hybrid Electric Vehicles (HEV). The introduction of lightly hybridized vehicles would not drastically alter the manufacturing process of conventional vehicles, thus limiting the overhead expense of modifications to assembly line fabrication by only introducing an incremental change. In order to achieve the goal of incremental change, the members of the IPRO will take into account results from an array of hybridization factors and concentrate on the realistic data ranges.

Team Organization

- **ADVISOR Simulations to acquire the best Hybridization Factor for HMMWV (High-Mobility Multipurpose Wheeled Vehicle) – Series Configuration:**
    - Antonis Antoniou, Justin Bench

- **ADVISOR Simulations to acquire the best Hybridization Factor for HMMWV (High-Mobility Multipurpose Wheeled Vehicle) – Parallel Configuration:**
    - Jonathan Komyathy

- **ADVISOR Simulations to acquire the best Hybridization Factor for HUMMER H3 – Parallel Configuration:**
    - Ovi Tisler, Mayank Bhatia

- **ADVISOR Simulations to acquire the best Hybridization Factor for HUMMER H3 – Series Configuration:**
    - Nikunj Panchal, Murat Ozcan, Brandon Seaton

- **ADVISOR Simulations to acquire the best Hybridization Factor for the Hybrid Electric Bus:**
    - Jeffery Parks, Steffany Evanoff, Trevor Waller

The sub-groups of the IPRO are working individually to come up with the best results for their particular vehicle. However, this does not mean that they are isolated from the rest of the group. There are plenty of entire group meetings where members can communicate with each other in order to acquire and share ideas.

<u>**Individual Group Descriptions and Progress**</u>

ADVISOR Simulations to find the best Hybridization Factor for HMMWV (High-Mobility Multipurpose Wheeled Vehicle) – Parallel *and* Series Configuration:

Abstract – Although commercial hybrid electric vehicles have been studied extensively, little has been done in the military vehicle section. This study is concentrated on the models that describe hybridized HMMWV vehicles and the simulation results of those models. Parallel and series configuration models have been created using a standard models found in the simulation software from NREL. Both a retrofit approach and a constant power approach has been tested and the results are compared to the conventional model results. In addition, the effect of using smaller engines than the existing, in a hybrid HMMWV has been studied and the results are compared to the data that have been collected from an actual implementation of such a vehicle. Moreover, the ISA configuration has been considered and the results were encouraging.

I. Introduction

In recent years, there have been many studies about the feasibility of commercial hybrid electric vehicles. These studies have concentrated their efforts on large vehicles with low fuel economy like Sports Utilities Vehicles (SUV) and other commercially available vehicles that fit those criteria. This study however will concentrate its effort on a widely used military vehicle the US Army High Mobility Multipurpose Wheeled Vehicle (HMMWV). In particular, this study will model and simulate hybrid versions of the M-1097A2 HMMWV which is used as a heavy cargo and troop carrier by various branches of the US armed forces and other countries.

II. Simulation Methodology

First, the model for a conventional HMMWV was constructed and simulated in order to have a standard base upon which comparisons of the hybridization results could be conducted. Then the models for the hybrid vehicles were constructed and simulated. There are two different configurations for hybrid electric vehicles, a series configuration and a parallel one. For each configuration, two different strategies were used. The first strategy kept the power of the vehicle constant and changed both the power of the internal combustion engine (ICE) and the power of the electric motor (EM) in order to achieve the proper hybridization factor (HF). The second strategy kept the power of the ICE constant and varied the power of the EM to achieve the desired HF. For each different configuration and strategy, three different drive cycles were used in order to simulate city driving, highway driving and a mix of the two. After the first round of simulations, a second round of simulations followed. During this second round of simulations, the series configuration simulations were repeated using a different engine in order to check the effects of different size engines. In addition to those simulations, a third configuration of hybrid vehicle was modeled and simulated. The third configuration used was the integrated starter alternator (ISA) configuration. In the third configuration, a single scaling strategy was used to achieve the desired HF; this strategy required the variation of the power of the ISA in order to achieve the requested HF.

III. Modeling Strategy

The software used to construct the models of the vehicles and simulate the models was the non-proprietary version of ADVISOR by the NREL. The models of the vehicles were constructed out of standard models that come with the version of ADVISOR that the team used. The method used in modeling the vehicles requires the various standard models to be scaled up or down in order for their properties to match the desired values. Because of this scaling of the models, the results of the simulations in which the models had to be scaled by a large factor should be used with caution, as the scaling of the properties of the model might not be as accurate as they should. Nonetheless, care was taken so that the models used had properties as close as possible as the properties required, before scaling.

A. Conventional HMMWV

The attributes of the base vehicle used are tabulated below. The model used for the ICE is the FC_I119 that produces 119kW maximum power and has a maximum torque of 400Nm. The model used for the transmission was the TX_AUTO4, which was slightly modified to have the exact gear ratios as the actual HMMWV. The wheel/axle model used was the WH_HEAVY. The team choose to use no accessory loads for the conventional HMMWV. The power-train control used for the conventional model was the PTC_CONVAT5spd.

Attribute	Value
Coefficient of Drag	0.5
Frontal Area	$3.58m^2$
Cargo Mass	2000kg
Cargo Height	0.808m
Front Axle Weight Percentage	0.4369
Glider Mass	2018kg
Gross Vehicle Weight (GVW)	4676kg
Wheelbase	3.3m

Table 1. Attributes of the conventional HMMWV

B. Parallel Configuration HMMWV

The attributes of the parallel configuration vehicle are the same as the conventional vehicle with the exception of the GVW that increases because of the addition of the EM and the batteries. The models used for the ICE, the transmission and the wheel/axle are the same as the ones used for the conventional vehicle. The EM model used is the MC_PM100_UQM that provides 100kW peak power without any scaling. The energy storage element used was the ESS_NIMH90_OVONIC, which is a model for a nickel metal hybrid battery that can store 1.1kWh of nominal energy. The model used for the power-train control was the PTC_PAR_AUTO, which sustains the charge of the battery at sixty percent. For the parallel configuration, the team decided to put a 700W constant load on the vehicle represented by the ACC_HYBRID accessory load.

C. Series Configuration

The attributes of the series configuration vehicle are the same as the conventional one except the GVW and the Cargo Mass. This two attributes changed from the first round of simulations to the second round of simulations. During the first round of simulations the cargo mass was constant while the GVW changed as the mass of the ICE, the mass of the EM and the mass of the storage element changed. In the second round of simulations the cargo mass changed in such a way as to keep the GVW constant. The models for the ICE, the wheel/axle, the EM, the storage element and the accessory loads were the same as in the parallel configuration model. The generator model used was the GC_PM63 that can provide a peak power of 63kW before scaling. The transmission model used was the TX_1SPD. The power-train control used was the PTC_shev_mv that keeps the charge of the storage element at forty percent constantly.

D. ISA Configuration

The attributes of the ISA configuration vehicle are the same except the cargo mass, which changes in such a way as to keep the GVW constant. The models used for the ISA configuration are the same models used in the parallel configuration except of the model for the EM. In the ISA configuration the model for the motor used was the MC_PM15_LYNX, which gives 15kW peak power without any scaling.

E. Drive Cycle configuration

Three different drive cycles were used during the simulations of each model. The first drive cycle was the Urban Dynamometer Driving Schedule (UDDS). This drive cycle is a representative drive cycle of city driving and it approximately 7.5 miles long. The first test for each model consisted of five continuous UDDS cycles. The second drive cycle used was the HighWay Fuel Economy Test (HWFET) cycle. This is cycle is approximately 10 miles long. The second test for each model consisted of five continuous HWFET cycles. The third drive cycle used was a mix of the previous two; it consisted of two UDDS cycles followed by two HWFET cycles and another UDDS cycle. This mix drive cycle was run only once because it consisted by five smaller drive cycles.

IV. Simulation Results
A. Conventional

The results for the conventional model are shown in the first column of table2; in the second column of the same table, the mileage and the acceleration along with the grade of an actual HMMWV are shown for comparison.

	Model	Actual
City Mileage (mpg)	10.8	11
Highway Mileage (mpg)	20.5	N/A
Mix Mileage (mpg)	14.1	N/A
0 – 50 mph (s)	27.3	26.1
Grade ability	32.1%	54%

Table 2. Conventional model mileage and performance results

Please note that the numbers presented on table2 for the actual vehicle have been put together through various sources. The mileage was calculated by dividing the cruising range of the vehicle by the amount of fuel its tank can hold. In addition, the grade ability of the vehicle was stated to be 54% on the manufacturer's website but the speed at which this grade is achieved is unknown. Having this in mind one can see from the results of table2 that the mileage of the model vehicle is very close to the actual mileage of the vehicle. Also, notice that the acceleration time from 0mph – 50mph is almost identical with the acceleration of the model being slightly slower. The grade ability of the model though deviates greatly from the grade ability of the actual HMMWV.

B. Parallel Configuration 1

The first method used to test the parallel hybrid configuration was one in which the total power of the vehicle was held constant. This means that the power of the internal combustion engine plus the power of the motor always equals 119 kW. Thus for each trial, the power of the motor and the power of the engine would change. One note about this method is that the number of batteries was not kept constant but was increased throughout the testing process to match the power of the electric motor, thus the gross vehicle weight was constantly increasing as more and more batteries were added. Table 3 contains the fuel economy results for this method while table 4 contains the performance results for this configuration. Note that the grade results are taken at fifty-five miles per hour.

HF	City (mpg)	Highway (mpg)	Mix (mpg)
5%	10.3	21.3	13.7
10%	10.8	21.9	14.3
15%	11.3	22.4	14.8
20%	11.5	22.8	15.1
25%	12.1	23.2	15.7
30%	12.9	23.8	16.5
35%	13.4	24.3	17.0
40%	14.1	24.8	17.7
45%	15.1	25.4	18.7
50%	15.6	26.2	19.3
55%	16.5	27.4	20.4
60%	17.6	28.6	21.6
65%	19.1	31.5	23.5
70%	21.3	35.8	26.5

Table 3. Fuel Economy for the parallel configuration model, method 1

HF	0 – 60mph (s)	Grade @ 55mph
5%	42.6	5.3
10%	38.1	4.9

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15%	33.6	4.5
20%	31.2	4.0
25%	29.4	3.5
30%	27.8	3.0
35%	26.6	2.6
40%	25.5	2.1
45%	24.7	1.6
50%	24.0	1.3
55%	23.4	0.9
60%	22.7	0.5
65%	22.1	0.1
70%	21.7	0.0

Table 4. Acceleration and Grade ability for the parallel configuration model, method 1

Chart B.1.1 Parallel Method 1 Fuel Economy

Chart B.1.2 Parallel Method 1 Highway Fuel Economy

Chart B.1.3 Parallel Method 1 Combined Fuel Economy
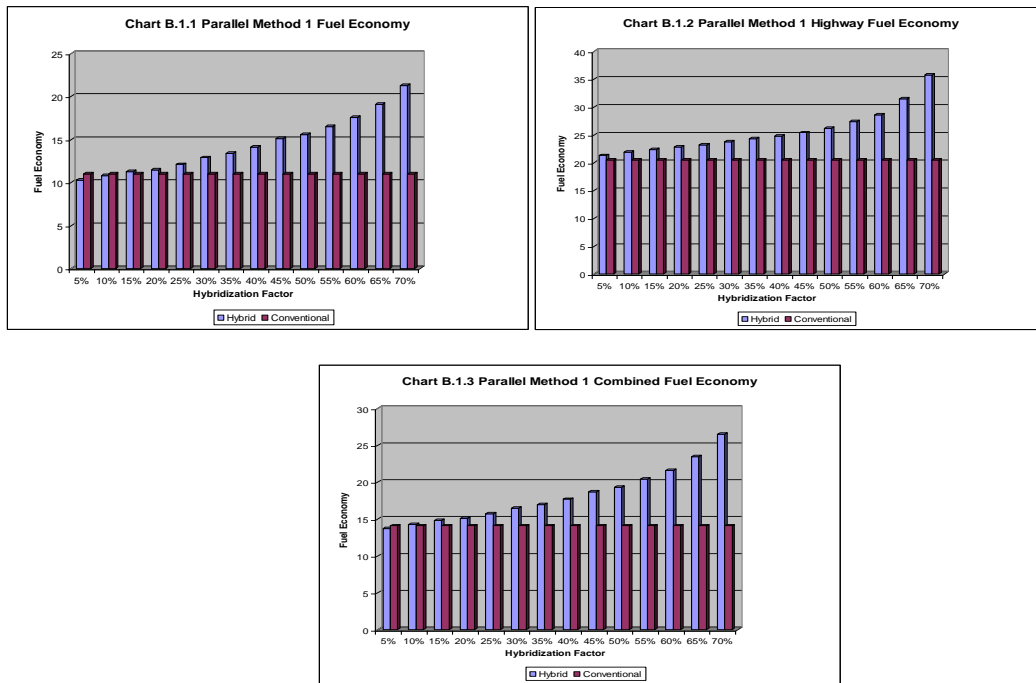
C. Parallel Configuration 2

The second method used to test the parallel hybrid configuration was one in which the power of the internal combustion engine was held constant. This means that the power of the internal combustion engine always equals 119 kW and the total power of the vehicle keeps increasing. Thus, for each trial, the power of the motor would be the only change. This method also changed the number of batteries to match the power of the electric motor, thus the gross vehicle weight was constantly increasing as more batteries were added. Tables 5 and 6 contain the fuel economy and performance results respectively.

HF	City (mpg)	Highway (mpg)	Mix (mpg)
5%	9.5	20.9	12.8
10%	9.5	21.0	12.9
15%	9.7	21.0	13.1
20%	9.8	20.9	13.2
25%	9.8	20.8	13.1
30%	9.6	20.7	12.9
35%	9.3	20.5	12.6
40%	9.0	20.7	12.3
45%	8.7	20.5	12.0

HF	City (mpg)	Highway (mpg)	Mix (mpg)
0%	15.5	19.5	14.5
5%	15.4	20.6	16.6
10%	14.3	21.8	16.7
15%	14.2	23.1	17.1
20%	13.7	25.5	18.8
25%	13.6	26.4	19.5
30%	13.7	28.4	21.0
35%	14.9	30.6	22.6
40%	16.3	33.3	24.6
45%	17.8	36.4	26.9
50%	19.8	40.2	29.7
55%	22.1	44.9	33.1
60%	24.5	49.7	36.6
65%	28.2	56.9	41.9
70%	33.1	66.9	49.0

Table 5. Fuel Economy for the parallel configuration model, method 2

HF	0 – 60mph (s)	Grade @ 55mph
5%	40.4	5.7
10%	34.8	5.7
15%	28.9	5.5
20%	25.6	5.4
25%	23.1	5.2
30%	21.1	4.9
35%	19.3	4.7
40%	N/A	4.5
45%	N/A	4.2

Table 6. Acceleration and Grade ability for the parallel configuration model, method 2

Chart B.2.1 Parallel Method 2 City Fuel Economy

Chart B.2.1 Parallel Method 2 Highway Fuel Economy
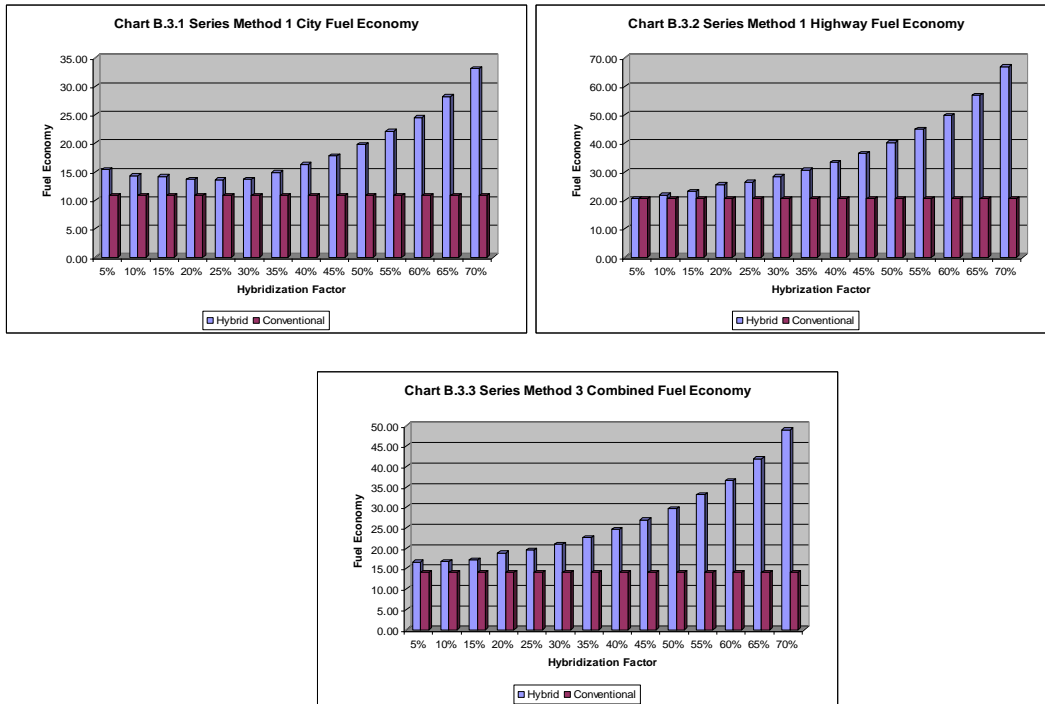

Chart B.2.3 Parallel Mehtod 2 Combined Fuel Economy
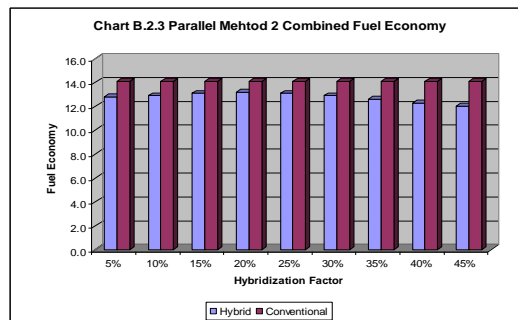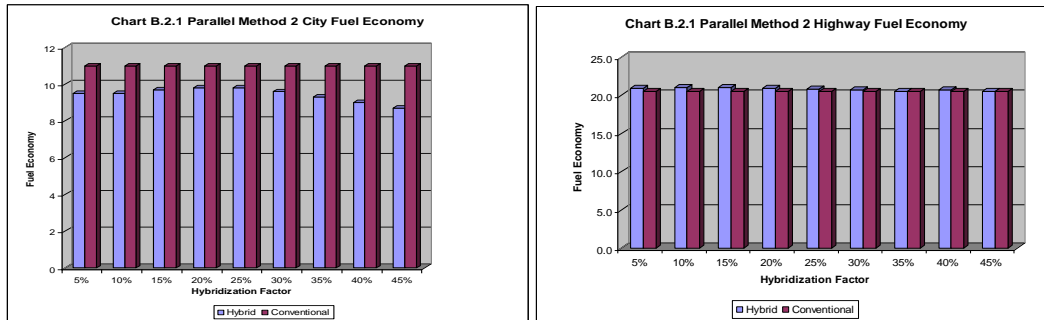
D. Series Configuration 1

The first method used to test the series hybrid configuration was one in which the power of the electric motor was held constant. This means that the power of the motor always equals 119 kW. Thus, for each trial, the power of the engine would change. One note about this method is that the number of batteries was kept constant at forty battery modules.

Table 7. Fuel Economy for the parallel configuration model, method 1

HF	0 – 60mph (s)	Grade @ 55mph
0%	17.7	
5%	17.7	10.80
10%	17.6	11.00
15%	17.5	11.00
20%	17.3	10.00
25%	17.3	9.70
30%	17.2	9.00
35%	17.1	8.30
40%	17.0	7.60
45%	16.9	6.90
50%	16.8	6.20
55%	16.8	5.40
60%	16.7	4.80
65%	16.6	4.00
70%	16.5	3.20

Table 8. Acceleration and Grade ability for the parallel configuration model, method 1

Chart B.3.1 Series Method 1 City Fuel Economy

Chart B.3.2 Series Method 1 Highway Fuel Economy

Chart B.3.3 Series Method 3 Combined Fuel Economy

D. Series Configuration 2

The second method used to test the series hybrid configuration was one in which the power of the internal combustion engine was held constant. This means that the power of the internal combustion engine always equals 119 kW and for each trial, the power of the motor would be the only change. This method held the number of batteries at a constant of twenty five modules.

HF	City (mpg)	Highway (mpg)	Mix (mpg)
-20%	17.90	19.10	13.60
-15%	18.20	19.00	13.50
-10%	18.10	18.90	13.50
-5%	18.00	18.90	13.40

0%	18.00	18.80	13.30
5%	17.90	18.80	13.30
10%	17.90	18.80	13.20
15%	17.80	18.80	13.20
20%	19.10	18.50	13.10

Table 9. Fuel Economy for the parallel configuration model, method 1

HF	0 – 60mph (s)	Grade @ 20mph
-20%	27.20	5.10
-15%	27.00	5.10
-10%	26.80	5.10
-5%	26.70	5.00
0%	26.60	5.00
5%	26.50	5.00
10%	26.50	4.90
15%	26.40	4.90
20%	26.40	4.90

Table 10. Acceleration and Grade ability for the parallel configuration model, method 1
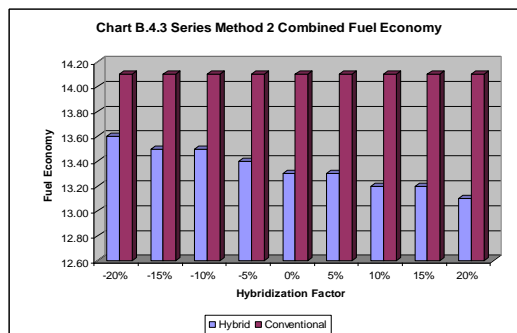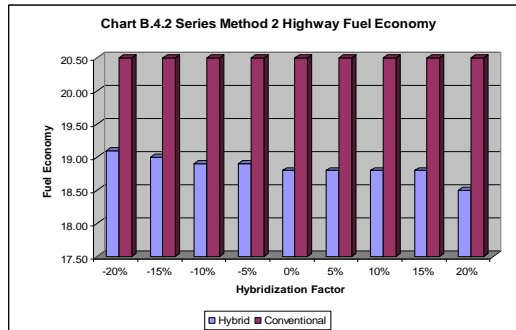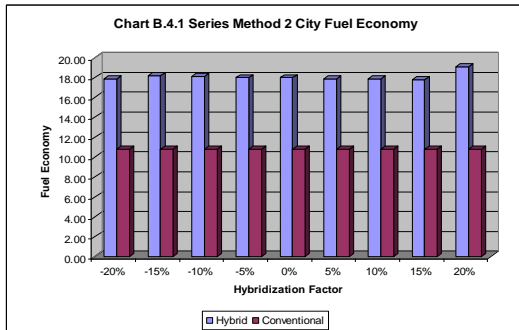
E. Series Configuration 3

In the third method for the series configuration the engine model used for the vehicle changed. In this method the model for a Volkswagen turbocharged diesel engine was uses. The power of the engine was kept constant and the power of the EM was varied in order to achieve the desired HF. In addition to this the weight of the vehicle of the vehicle was kept constant by varying the weight of the cargo. A constant number of twenty battery modules were used.
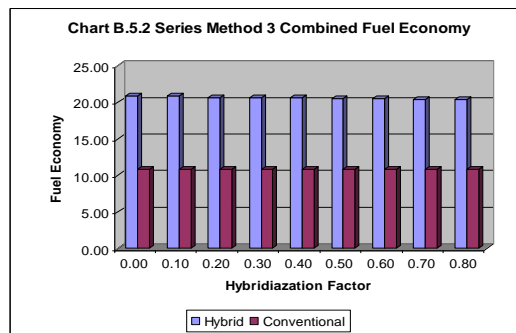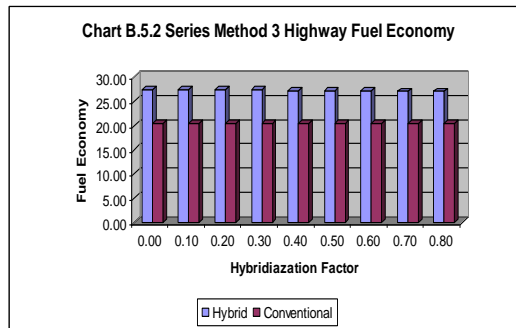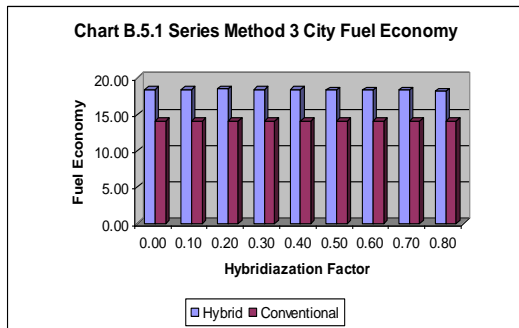
HF	City (mpg)	Highway (mpg)	Mix (mpg)
0.00	18.40	27.40	20.90
0.10	18.40	27.30	20.90
0.20	18.50	27.30	20.60

0.30	18.40	27.30	20.60
0.40	18.40	27.20	20.60
0.50	18.30	27.10	20.50
0.60	18.30	27.10	20.50
0.70	18.30	27.00	20.40
0.80	18.20	27.00	20.40

Table 11. Fuel Economy for the Series configuration model, method 3

HF	0 – 60mph (s)	Grade @ 9mph
0.00	26.00	10.80
0.10	25.10	10.80
0.20	24.50	10.80
0.30	24.10	10.80
0.40	23.80	10.80
0.50	23.50	11.00
0.60	23.30	11.90
0.70	23.10	12.80
0.80	22.90	13.70

Table 12. Acceleration and Grade ability for the ISA configuration model

Chart B.5.1 Series Method 3 City Fuel Economy

Chart B.5.2 Series Method 3 Highway Fuel Economy

Chart B.5.2 Series Method 3 Combined Fuel Economy

F. ISA Configuration

In the ISA configuration the power of the engine was kept constant and the power of the ISA was varied in order to achieve different hybridization factors. During these simulations the minimum amount of battery modules was used in order to meet the drive cycles. Also during these simulations the total weight of the vehicle was kept constant by constantly varying the weight of the cargo.

HF	City (mpg)	Highway (mpg)	Mix (mpg)
0.17	14.40	29.00	19.00
0.14	14.30	29.00	18.90
0.11	14.20	29.00	18.80

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0.08	14.20	28.90	18.70
0.07	14.20	28.90	18.80
0.04	14.10	29.00	18.70
0.02	14.10	29.00	18.70

Table 13. Fuel Economy for the ISA configuration model

HF	0 – 60mph (s)	Grade @ 9mph
0.17	7.30	40.90
0.14	8.20	41.30
0.11	8.20	41.80
0.08	8.20	42.30
0.07	8.20	42.40
0.04	8.20	3.20
0.02	8.20	5.80

Table 14. Acceleration and Grade ability for the ISA configuration model

Chart B.6.1 ISA City Fuel Economy

Chart B.6.2 ISA Highway Fuel Economy

Chart B.6.3 ISA Combined Fuel Economy
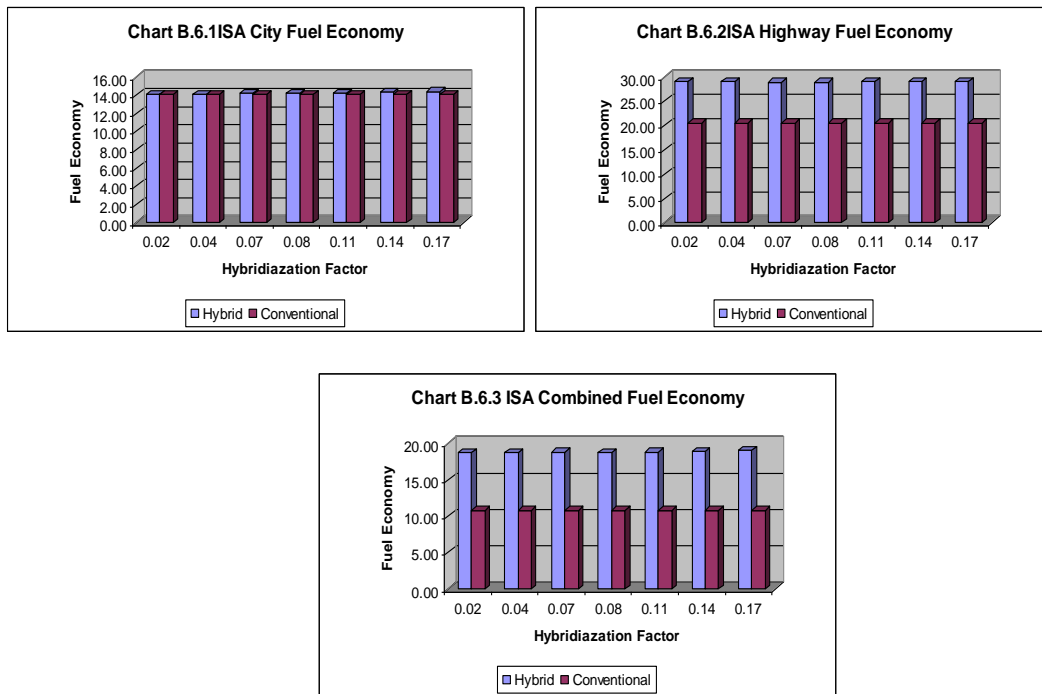
V. Conclusions

Comparing both the series and parallel results one can clearly observe that the best method of hybridization is the customization of both the power of the EM and the ICE in order to achieve the HF desired. This trend is due to the extra engine weight that exists in the second method of hybridization. This is true for the first method also, however, in the first method most of the weight gained because of the batteries and the EM, is lost from the downsizing of the engine. Thus this slight gain in mass is out weighted by the increase in fuel efficiency caused by the smaller engine size. This observation is also clear from the results in the third method of the series configuration, when the model of the vehicle is outfitted with the smaller Volkswagen engine that has a better power output to weight ratio. The smaller engine size coupled with the an EM that has the same power output as the original engine allows for 100% increase in the fuel efficiency of the vehicle. In addition to the increase in fuel efficiency, one can also observe a decrease in acceleration time for the 0mph to 60mph interval and an increase in maximum speed. This decrease in acceleration time and increase of maximum speed comes about because of the nature of the EM. The EM is a machine that provides relatively constant power at a variable speed and torque, thus vehicles equipped with an electric

motor can achieve higher speeds and can also accelerate faster because at the lower speeds the EM provides higher torque and thus better initial acceleration. However, this increase in acceleration and speed performance is accompanied by decreased grade ability. This decreased grade ability is also caused by the nature of the EM. As stated above the EM provides fairly constant power by varying both speed and torque, thus at higher speed the torque provided by the EM is significantly less than the torque provided by an ICE at the same speed. This decreased torque at higher speed means that the vehicle has a reduced ability to negotiate climbs at higher speeds. This trend becomes clearer as the HF increases, causing the EM size to increase and the ICE size to decrease. Because of the decreased size of the ICE the torque of the system is decreased and thus the grade ability also decreases. In the series configuration where the EM is directly coupled to the wheels of the vehicle and thus the multiplication of torque provided by the transmission is removed this decrease in grade ability is more pronounced. Having made these observations one would suggest that a low hybridization factor, between 0.1 and 0.4 would be ideal for the HMMWV. This degree of hybridization would provide an increase in fuel efficiency without a huge sacrifice of grade ability and towing capability that is so important to a military vehicle. Of course higher hybridization factors could be implemented on this type of vehicle but specially designed, high torque, motors would be required in order to achieve the desired results and keep the vehicle up to specification. An alternative approach would also suggest using a special transmission that would only be invoked in cases where higher torque and less speed are required. However, hybridization using a distinct electric motor is not the only option. As the ISA configuration suggests a 75% increase in fuel economy is possible for mixed conditions if we use a small electric motor as an ISA. Such a configuration also provides increase grade ability and acceleration. This increase in both aspects of performance is caused by the nature of the configuration. The directly coupled electric motor provides extra torque at all times causing the grade ability of the vehicle to rise significantly. In addition to that, this extra torque is at a maximum at lower speeds thus a vehicle with an ISA has a large amount of torque compared to a conventional one when it is starting to move from a stand still. This huge amount of torque can be used to accelerate the car to high speeds in a shorter time period.

ADVISOR Simulations to find the best Hybridization Factor for HUMMER H3 – Parallel *and* Series Configuration:

I. INTRODUCTION

The Hummer H3 was a relatively fuel efficient vehicle in its class, with approximate fuel economy numbers in the range of 16 miles per gallon in the city and 20 miles per gallon on the highway. This data could not be verified with actual test results, but we depended on the data obtained from various online sources and GM, especially at www.hummer.com. The Hummer H3 is built with the following components and these were the parameters that the group depended on the most in order to model a representative HUMMER. Please refer to table I for a detailed description of the Hummer H3.

TABLE I
CONVENTIONAL HUMMER H3

Components	Hummer H3
Engine	Vortec 3500 3.5L inline 5 cylinder
Vehicle Power	220hp(164kW) @ 5600 rpm
Torque	225 lbs.-ft (305 Nm) torque @ 2800 rpm
Transmission	Full time 4WD Automatic
Coefficient of Drag.	0.5
Vehicle Mass	4700 lbs (2136 kg)
Vehicle Frontal Area	5565.4 in sq. (w/o mirrors) (3.591 m^2)
Vehicle Wheel Base	112 in. (2.84 m)
Vehicle's Center of Gravity.	0.74 m

The data is taken from GM sources

The expectations were to see improvements in fuel economy numbers by hybridizing the H3. However, the main focus was to research into its performance. It has widely been held that hybrid vehicles do not obtain good performance numbers relative to their conventional counterparts; the aim was to look deeper into this myth and come up with practical solutions for the performance problems. To make this a viable option for auto manufacturers, the group also did a cost benefit analysis. It should also be noted that hybridizing a

vehicle also gives the consumer the option to drive 4-wheel, or all wheel, whatever happen to be the requirements of the consumer. Generally car companies charge a premium for all wheel drive, and without substantial addition to this premium the consumers can also enjoy the cost saving benefits of a hybrid vehicle.

II. VEHICLE DEFINTION

As already described in the introduction, the group was trying to model the Hummer H3 for the intended research. For this purpose we chose a 95 kW Saturn DOHC and SOHC Four Cylinder Engine. This was a Gasoline Spark Ignition, 1.9L engine with a peak efficiency of 35%, the engine was then scaled up to the 164kW required for the Hummer H3. Numerous other engines were also considered, however, this one was chosen because the torque speed characteristics of this engine matched closely to that of the Hummer H3.

TABLE 2
REPRESENTATIVE HUMMER H3

Components	Hummer H3
Engine	95 kW Saturn Gasoline Spark Ignition, 1.9L(FC_SI95.m)
Vehicle Power	220hp(164kW) @ 5600 rpm
Torque	225 lbs.-ft (305 Nm) torque @ 2800 rpm(TC_DUMMY)
Transmission	Full time 4WD Automatic
Coefficient of Drag.	0.5
Vehicle Mass	4700 lbs (2136 kg)
Vehicle Frontal Area	5565.4 in sq. (w/o mirrors) (3.591 m^2)
Vehicle Wheel Base	112 in. (2.84 m)
Vehicle Cargo Mass (Payload)	300 kg
Vehicle's Center of Gravity.	0.74 m

The data is used to simulate our representative H3 selection criteria is explained above.
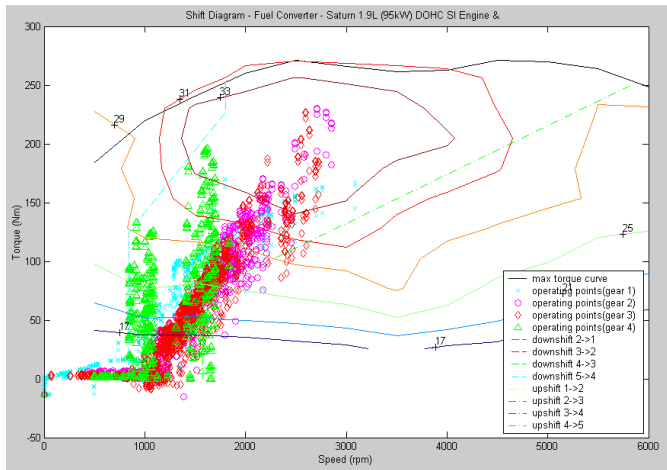

Fig. 1. The Torque speed characteristics of the representative H3.

Also this engine gave the closest fuel efficiency to that of the HUMMER H3 (the engine operated between 17% to 35%) numbers when this engine was simulated with the conventional drive train configuration. The fuel converter file used in ADVSIOR was FC_SI95.m. Some drawbacks to using this engine could be that the actual engine was a 3.5 L , in-line 5 cylinder engine, while the Saturn engine was a 1.9L, 4 cylinder vehicle, but due to lack of comprehensive data from the manufacturers of Hummer H3(since at the time of writing of the paper H3 hadn't been released yet) the decision was to go with this compromise as the two main components of our research, namely the fuel efficiency and the performance characteristics matched closely with that of the Hummer H3.

The Hummer H3 comes in both a 5-speed manual and automatic transmissions. But since the vehicles with automatic transmissions are more popular it was decided to simulate our representative vehicle with an automatic transmission. For this purpose we used the TX_AUTO4 transmission for our parallel simulations, and the TX_AUTO1 for series built into ADVISOR. They are not the same because as will be explained later, the series hybridization does not require a transmission and moreover the TX_AUTO4 was giving anomalous results; this was attributed to the transmission and hence it was adjusted.

The vehicle mass of the representative HUMMER slightly lower than that of the conventional vehicle, thus and additional 300kg of cargo mass was added to compensate for the difference. Therefore, in all of the simulations, the cargo mass was kept constant at 300kgs.

Other constants that we changed for the simulations included, Coefficient of drag to 0.5, and the wheelbase to 2.84m, which corresponded to the H3. Thus, table 2 will be used to summarize the vehicle definitions.

Other factors which were used during the simulation of this vehicle include, torque coupling which was a built in module in ADVISOR, called TC_DUMMY. Besides this the group also used standard wheel/axle configurations for SUVs as WH_SUV module built into ADVISOR. The conventional exhaust for gasoline vehicles which was used is called EX_SI. When the representative Hummer H3 was simulated the following results were obtained (tabulated in Table 3).

The drive cycle used for the city simulations was the urban dynamometer driving schedule (UDDS). Each instance was simulated for 5 UDDS cycles to get the final fuel economy number. The snapshot of the UDDS drive cycle is shown below in figure 2.

TABLE 3
REPRESENTATIVE HUMMER H3 SIMULATION DATA

Parameters	Representative Hummer H3
Miles/Gallon City	15.4 miles
Miles/Gallon Highway	22.1 miles
Miles/Gallon Combination of 3city and 2highway	18 miles
0-60 miles/hour	11.1 seconds
40-60 miles/hour.	5.6 seconds
Quarter Mile	18.1 seconds
Gradability	15%

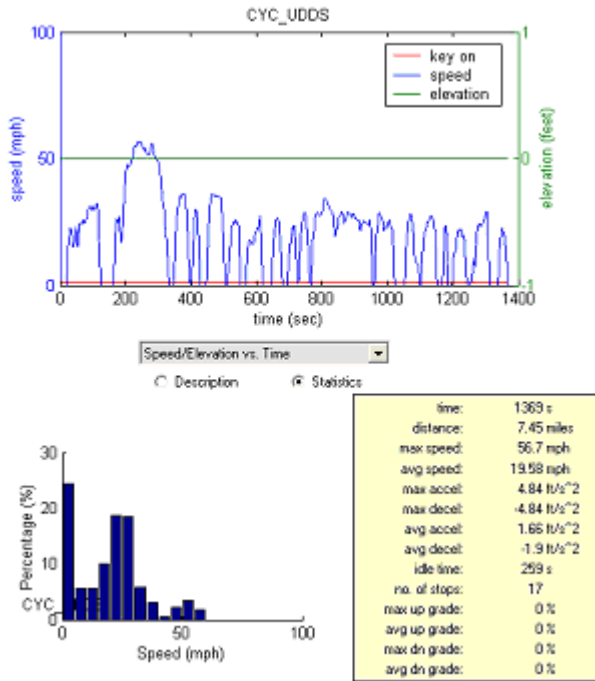The data is obtained by simulating our representative Hummer H3.

Fig. 2. The UDDS Drive cycle snapshot.

The drive cycle used for the simulation for the highway results was the HWFET drive cycle which is built into ADVISOR, the vehicle was also simulated for 5 cycles. It should be noted here in passing that the National Renewable Energy Laboratory and the US department of Energy both use the UDDS and the HWFET drive cycles to test vehicles. A snapshot of the HWFET drive cycle is presented below.
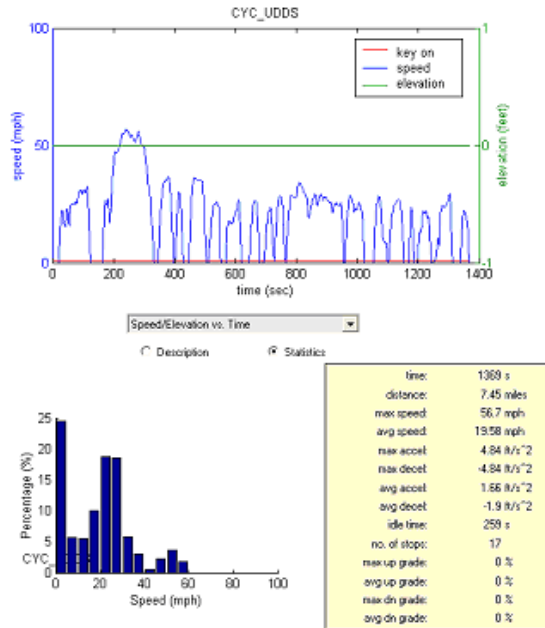

Fig. 3. The HWFET Drive cycle snapshot.

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Besides this another drive cycle was created, it is called the COMBO drive cycle which consisted of 3 UDDS and 2 HWFET drive cycles. The snapshot of the COMBO drive cycle is presented in figure 4.
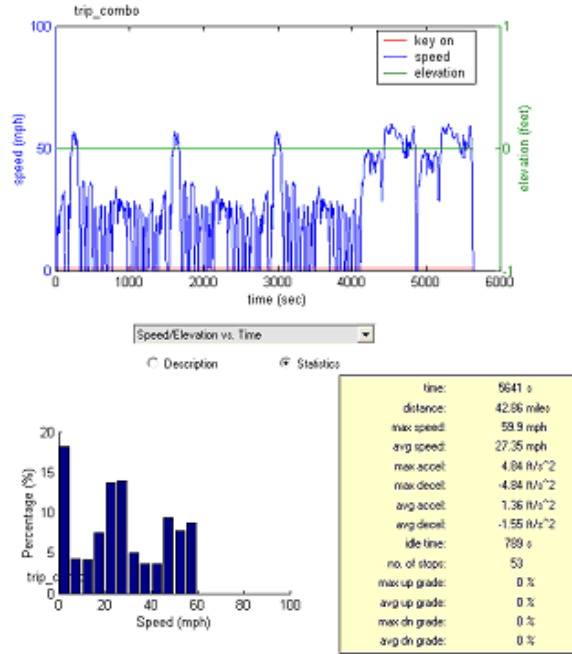
Fig. 4. The COMBO Drive cycle snapshot.

The combo was simulated for only one drive cycle because it was already comprised of 5 drive cycles.

III.   ADVISOR

Advisor is a program that demonstrates the importance of vehicular systems analysis. Vehicular systems analysis is crucial to the efforts of the advancement of hybrid electric vehicles. Advisor provides accurate and flexible tools to analyze and optimize vehicle components before it is produced by the auto manufacturer. This allows individuals to use the software to model a conventional vehicle, and then attempt to optimize it by changing various components. For the HUMMER H3, the group used the components illustrated in table 2 to model the vehicle in advisor. All of these parameters can be inserted into the advisor's user interface. Advisor's interface is a simple to use Graphical User Interface (GUI) with several drop-down menus where information can be altered.

Fig. 5. ADVISOR Screenshot.

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Figure 5. represents a basic Advisor screen shot. All of the drop-down menus represent parameters that can be changed in almost any way to 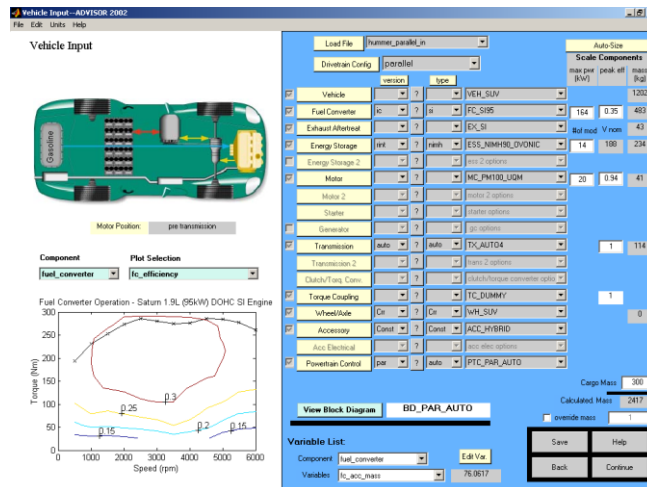change the performance/fuel efficiency of the vehicle. Although some of the parameter names seem cryptic, they can be examined by viewing the source code of the file. By clicking on one of the yellow buttons on the left of the input area, you can open a number of different source code files that correspond to the component that was selected. The source code has information that is pertinent to properly modeling a vehicle. For example, if a 100kW diesel fuel converter is needed to model a particular vehicle, one would need to search the source code files to find which engines represent diesel engines, and moreover, one would need to match the size of the engine. For the H3, the group first had to model the conventional HUMMER H3. The difficulty in this is that the H3 has not yet come out; therefore, many specifics were not available. The group had to estimate a couple of the parameters of the vehicle, and therefore the results that were obtained from the Advisor simulations reflect only a representative H3. No precise numbers for fuel economy or acceleration are available for the H3, so the group modeled the H3 as closely as it could to the estimates given by several sources. All in all, Advisor is a powerful program that will accurately model vehicles, both conventional, as well as hybrid electric. The interface allows users to alter the parameters to optimize the results, and this saves a lot of time and money for auto manufacturers. The program is a practical tool that lets auto manufacturers find out how to optimize their vehicles on computer rather than run expensive and extensive real-life simulations.

IV.   SIMULTION METHODOLOGY

There are two popular methods of hybridizing a vehicle which are currently in use:
- a.   Parallel Hybridization.
- b.   Series Hybridization.

a. Parallel Hybridization- This is the most practical method of hybridizing a vehicle. The parallel hybrid is an HEV in which more than one energy converter can provide propulsion power. Propulsion basically means the total output provided by the electric motor and conventional Internal Combustion Engine. $P_{motor}+P_{engine}$=Propulsion.

To explain the parallel drive train configuration lets first examine the conventional drive train. Figure 6. shows the ICE (Internal combustion engine) drive train.
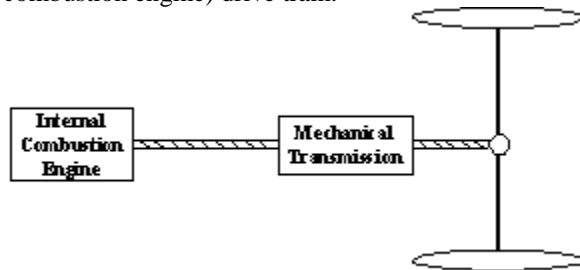
Fig. 6. Conventional Drive Train Configuration.

The above figure is a very simplified representation of a conventional vehicle. From figure 6. it is visible that there are only mechanical connections between the engine and the wheels. In passing, it must be mentioned that the efficiency of mechanical systems as compared to their electrical counter-parts is extremely low. While an Internal Combustion Engine (gasoline) peaks at around an efficiency of 35%, the average efficiency of an electrical system is at least 80%. Thus, we can see the energy savings from this perspective. Also some might make a case about the advantages of a fully electric car, but this is not a feasible idea given the current technology available in energy storage. It is estimated that the battery in a fully electric vehicle needs to be recharged for 8 hours after every 100 miles. So, any hybrid technology that does not overhaul the current design completely and yet increases fuel efficiency seems like a more viable option.

Lets now look into the parallel drive train configuration. Figure 7. represents a hybrid electric vehicle with a parallel drive train.

Fig 7. Parallel Hybrid Drive train.

This is a very viable option as it allows for regenerative breaking and also allows us to operate the ICE at it peak efficiency. Generally ICE's perform best at a given power rating and constant variance in the power output causes the efficiency to decrease. Therefore it has been noticed when cars are driven at a constant speed (usually around 50 mph) a much better fuel efficiency is obtai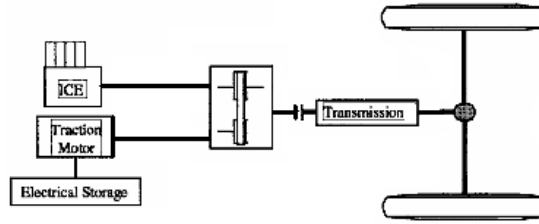ned, than if the speed were constantly varied. But it cannot be expected that cars will be driven at a constant speed. This problem is also solved by the parallel hybridization. Lets assume that in figure 7. the total power of the vehicle is a 100hp; out of which 50 is obtained from the ICE (the peak efficiency level is 50 for the ICE used) and the remaining 50hp from an electric motor. Lets say the vehicle need to derive 60 hp from the engine, this is achieved by getting 50hp from the ICE (its always producing 50hp) and the remaining 10hp from the motor. But what if 40hp is required? The ICE is always producing 50hp, but in this case the 50 hp is produced from the ICE in the following way:

40hp from the ICE goes to the wheels while the remaining 10hp is redirected to the electrical machine, which now acts as a generator instead of a motor and uses this power to charge batteries. Thus saving fuel and charging the battery at the same time.

The major advantages of parallel drive train configuration are as follows: -
- Using the ICE at its peak efficiency.
- Smaller ICE, therefore cost savings.
- Regenerative breaking for charging the battery modules.

While simulating the parallel hybrid drive train two different methods were used. Method I was achieved by keeping the total power of the vehicle constant and by varying the power of the engine (ICE) and the electric motor. In Method II we kept the power of the engine (ICE) constant and varied the power from the electric motor, this in turn increased the total power of the vehicle. Method II is also known as the retrofit approach. The relationship between the power emitted by the ICE and the electric motor is known as the hybridization factor (HF). For Parallel Drive Train the hybridization factor is defined as:

$$ HF = \frac{P_{MOTOR}}{P_{MOTOR} + P_{ENGINE}} \qquad (1) $$

P_{MOTOR} stands for the power of the electric machine while P_{ENGINE} is for the Power generated by the ICE.

b. Series Hybridization – The series hybrid is also a very popular method of hybridizing. Figure 8. shows a simple series hybrid.
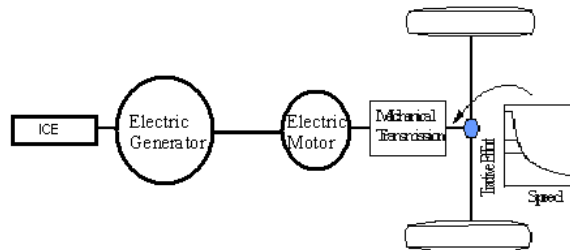
Figure 8. Series Hybrid Configuration.

The major differences between a series and the parallel hybrid configurations are that 2 electric machines (the motor and the generator) are being used, They are connected with electrical connectors thus they are more efficient in cascading the energy from the ICE to the wheels than a conventional mechanical connection. The hybridization factor for a series is defined as: -

$$HF = \frac{P_{MOTOR} - P_{ENGINE}}{P_{MOTOR}} \quad (2)$$

Also like the parallel configuration the series hybrid was simulated as per the same two methods as described earlier.

V.   TEST RESULTS FOR PARALLEL SIMULATIONS

It should be mentioned that since electric machines are used, additional energy would be needed to run those electric machines. This was provided by additional battery modules to the vehicle. The standard Lead Acid batteries are not enough to drive the motor so Nickel Metal Hydride (NiMH) batteries manufactured by Ovonic were used instead. These modules are designed to be high power, intermediate energy battery units and thus it was the clear choice for the simulations. Other technical specifications of the battery are explained below:

- Cell type = M155
- Nominal Voltage = 12V
- Nominal Capacity (C/3) = 90Ah
- Dimensions (L * W * H) = 385mm X 102mm X 168mm
- Weight = 16.7kg
- Volume (modules only) = 6.1L
- Nominal Energy (C/3) = 1100 Wh
- Peak Power (10s pulse @ 50%DOD @ 35 deg. C) = 7.0kW

The Westinghouse 75 kW AC Induction motor was capable of delivering a maximum power of with an efficiency of 92%, thus it was selected for the simulations. The mass of the motor was relatively low at 91kgs compared to the total mass of the car, which stood at 4700lbs. The torque speed map of the motor is presented below in figure 9.
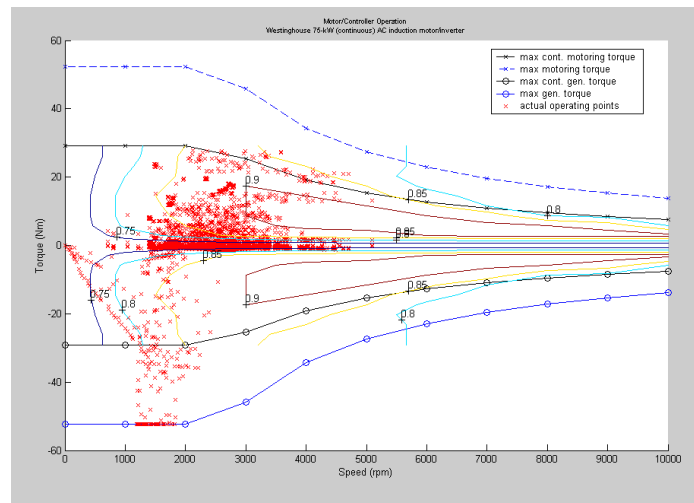
Fig 8. Torque Speed plot of the motor.

It can be noticed from figure 8. that the induction motor operates in a very high efficiency region at around 85%. Also figure 9 shows the efficiency of the motor at various operating points.
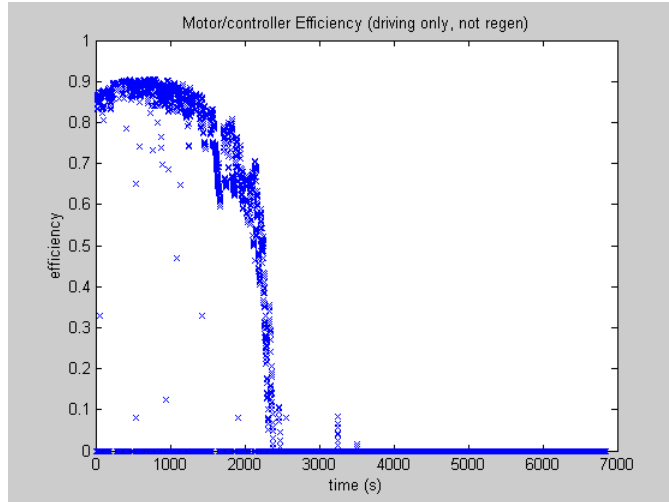
Fig 9. Efficiency of the motor(AC75).

Parallel method I was simulated for a hybridization factor (HF) in the range of 0 to 0.70, with increments of 0.05 units for each simulation. Once this was done the team searched for the optimal hybridization factor which yielded good fuel efficiency improvements as well as good performance. There was definitely a tradeoff in choosing between performance and efficiency. At higher HF levels the fuel efficiency increases were significant, but this led to poor performance numbers, which is not an ideal solution. So the group focused its efforts on maintaining if not increasing the performance, while considering the fuel efficiency as a secondary measure. Also once the HF range was obtained where the performance numbers were deemed optimal, more simulations were run in that specific range with increments of 0.01 HF, so that the best hybridization factor within the precision of one unit could be obtained. The overall results from parallel method I are presented in table 4, and the precision numbers are presented in table 5. Also figures 10 and 11 show the respective percentage changes for the HF levels. According to simulations it was discovered that the best hybridization factor would be between 0.20 to 0.30. According to criteria described above, it was found that 0.20 was the best HF. The results at 0.20 HF are summarized below:

- Fuel Economy at HF = 0.20
  - City: 20.4 MPG (32.46% increase)
  - Highway: 26.7 MPG (20.81% increase)
  - Combo: 22.9 MPG (27.22% increase)
- Performance at HF = 0.20
  - 0-60: 9.2s (17.17% increase)
  - ¼ mile: 17 (6.07% increase)
  - Gradeability: 10.20% (32.89% decrease.)

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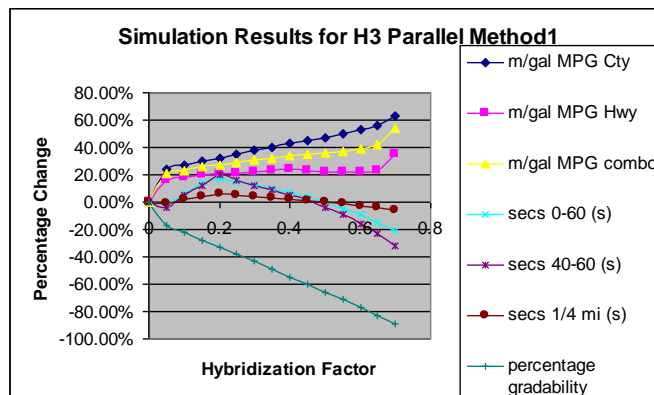
Fig 10. Hummer H3 percent change in different parameters.

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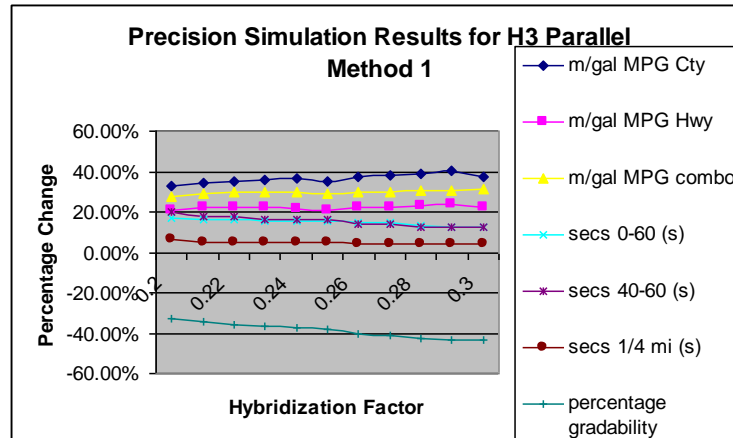
Fig 11: hummer h3 percent change precision data.

TABLE 4. PARALLEL METHOD I SIMULATION RESULTS.

ratio	KW	KW	m/gal	m/gal	m/gal	secs	secs	secs	percentage
HF	Enigne (kW)	Motor (kW)	MPG Cty	MPG Hww	MPG comb	0-60 (s)	40-60 (s)	1/4 mi (s)	gradability
0	164	0	15.4	22.1	18	11.1	5.6	18.1	15.20%
0.05	155.8	8.2	19.1	25.7	21.8	11.2	5.8	18.2	12.60%
0.1	147.6	16.4	19.6	26.1	22.2	10.4	5.3	17.7	11.90%
0.15	139.4	24.6	20	26.5	22.7	9.6	4.9	17.3	11.00%
0.2	131.2	32.8	20.4	26.7	22.9	9.2	4.5	17	10.20%
0.25	123	41	20.8	26.7	23.2	9.4	4.7	17.2	9.40%
0.3	114.8	49.2	21.2	27	23.6	9.7	4.9	17.3	8.60%
0.35	106.6	57.4	21.5	27.1	23.8	10	5.1	17.5	7.80%
0.4	98.4	65.6	22	27.3	24.2	10.3	5.3	17.7	6.90%
0.45	90.2	73.8	22.4	27.1	24.3	10.7	5.5	17.9	6.10%
0.5	82	82	22.7	27	24.4	11.1	5.8	18.1	5.20%
0.55	73.8	90.2	23.1	26.9	24.7	11.6	6.1	18.3	4.40%
0.6	65.6	98.4	23.6	26.9	25	12.1	6.5	18.6	3.50%
0.65	57.4	106.6	24.1	27.1	25.6	12.8	6.9	18.9	2.60%
0.7	49.2	114.8	25.1	29.8	27.7	13.4	7.4	19.2	1.70%

TABLE 5: PARALLEL METHOD I PRECISION SIMULATION RESULTS

ratio	KW	KW	m/gal	m/gal	m/gal	secs	secs	secs	percentage
HF	Enigne (kW)	Motor (kW)	MPG Cty	MPG Hww	MPG comb	0-60 (s)	40-60 (s)	1/4 mi (s)	gradability
0.2	131.2	32.8	20.4	26.7	22.9	9.2	4.5	17	10.20%
0.21	129.56	34.44	20.7	27	23.2	9.3	4.6	17.2	10.00%
0.22	127.92	36.08	20.8	27.1	23.4	9.3	4.6	17.2	9.80%
0.23	126.28	37.72	20.9	27	23.3	9.4	4.7	17.2	9.60%
0.24	124.64	39.36	21	26.9	23.4	9.4	4.7	17.2	9.50%
0.25	123	41	20.8	26.7	23.2	9.4	4.7	17.2	9.40%
0.26	121.36	42.64	21.2	27	23.3	9.5	4.8	17.3	9.10%
0.27	119.72	44.28	21.3	27	23.4	9.5	4.8	17.3	9.00%
0.28	118.08	45.92	21.4	27.2	23.5	9.6	4.9	17.3	8.70%
0.29	116.44	47.56	21.6	27.3	23.5	9.7	4.9	17.3	8.60%
0.3	114.8	49.2	21.2	27	23.6	9.7	4.9	17.3	8.60%

TABLE 6: PARALLE RETROFIT SIMULATION RESULTS.

ratio	KW	KW	m/gal	m/gal	m/gal	secs	secs	secs	percentage
HF	Enigne (kW)	Motor (kW)	MPG Cty	MPG Hwy	MPG comb	0-60 (s)	40-60 (s)	1/4 mi (s)	gradability
0	164	0	15.4	22.2	18	11.1	5.6	18.1	15
0.05	164	9	18.5	25.3	21.2	10.7	5.5	17.9	13.3
0.1	164	18	18.4	25.3	21.1	9.5	4.8	17.2	13.3
0.15	164	29	18.2	25.1	20.9	8.6	4.2	16.7	13.2
0.2	164	41	18	24.8	20.7	8.4	4	16.5	13.1
0.25	164	55	17.7	24.6	20.4	8.4	4	16.5	13
0.3	164	70	17.4	24.2	20	8.3	4	16.5	12.9
0.35	164	88	17.1	23.9	19.7	8.3	3.9	16.5	12.8
0.4	164	109	16.8	23.6	19.4	8.3	3.9	16.5	12.6
0.45	164	134	16.4	23.2	19	8.3	3.9	16.5	12.5
0.5	164	164	16	22.7	18.6	8.4	4	16.5	12.3

TABLE 7: PARALLEL RETROFIT PRECISION RESULTS.

ratio	KW	KW	m/gal	m/gal	m/gal	secs	secs	secs	percentage
HF	Enigne (kW)	Motor (kW)	MPG Cty	MPG Hwy	MPG comb	0-60 (s)	40-60 (s)	1/4 mi (s)	gradability
0.05	164	9	18.5	25.3	21.2	10.7	5.5	17.9	13.3
0.06	164	10	18.5	25.3	21.2	10.5	5.4	17.8	13.3
0.07	164	12	18.5	25.3	21.2	10.3	5.2	17.6	13.3
0.08	164	14	18.5	25.3	21.2	10	5.1	17.5	13.3
0.09	164	16	18.5	25.3	21.2	9.8	5	17.4	13.3
0.11	164	20	18.4	25.2	21.1	9.3	4.7	17.1	13.3
0.12	164	22	18.4	25.2	21.1	9.2	4.6	17	13.3
0.13	164	25	18.3	25.2	21	8.9	4.4	16.9	13.2
0.14	164	27	18.3	25.2	21	8.7	4.3	16.8	13.2
0.15	164	29	18.2	25.1	20.9	8.6	4.2	16.7	13.2

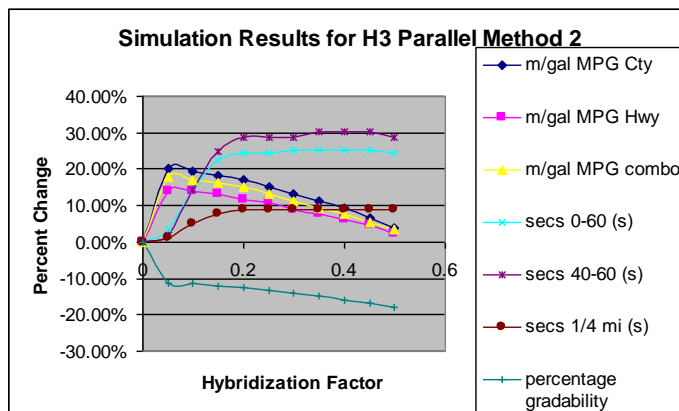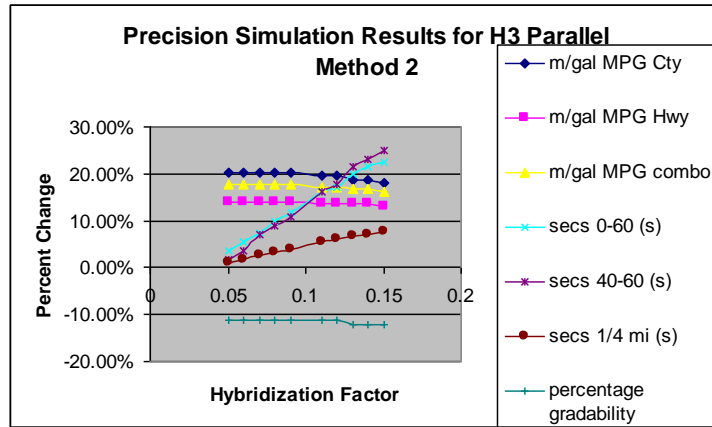Fig. 12. HUMMER h3 percent change.

Fig. 13. HUMMER h3 percent change precision data.

Table 6 and 7 present the data obtained from the retrofit approach for the parallel hybrid simulations. As explained earlier the group selected a range for this simulation as well, and this time the range selected was between 0.10 HF to 0.15 HF, then the precision simulations were carried out and it was determined that the best HF for the retrofit approach using the parallel hybrid simulations was 0.15 HF. Therefore to summarize the results for the Parallel Retrofit approach: -

- Fuel Economy at HF = 0.15
    - City: 18.2 MPG (18.2% increase)
    - Highway: 25.1 MPG (13.1% increase)
    - Combo: 20.9 MPG (16.1% increase)
- Performance at HF = 0.15
    - 0-60: 8.6s (22.5% increase)
    - ¼ mile: 16.7 (7.74% increase)
    - Gradeability: 13.2 (12% decrease.)

Figures 12 and 13 represent the percent changes from the representative conventional base vehicles

VI.   TEST RESULTS FOR SERIES SIMULATIONS

The definition for the hybridization factor for series configuration has been described in the previous sections. Also as explained earlier the generator was needed for the series simulations. The generator selected for the simulations was a 95% efficient inductive generator, and the built-in module in ADVISOR was named GC_ETA95. Other differences from the parallel simulations included:

The transmission which was used for the series method was the TX_AUTO1 and the control strategy selected was PTC_SER, which is the optimized series drive train. The series Method I was simulated from HF of 0 to 0.70, and the series retrofit approach was simulated from HF of -0.20 to 0.20. The series simulations did not yield good results as was expected for the performance data. One of the possible reasons for this anomaly could be because 2 electric machines were being used, and yet, the simulations were conducted with the minimum number of energy storage modules. Also the power train control strategy of PTC_SER is not as efficient as the one used for parallel. However, the fuel efficiency numbers were excellent. The results are presented below.

TABLE 8: SERIES METHOD I SIMULATION RESULTS.

ratio HF	KW Enigne (kW)	KW Motor (kW)	m/gal MPG Cty	m/gal MPG Hwy	m/gal MPG comb	secs 0-60 (s)	secs 40-60 (s)	secs 1/4 mi (s)	percentage gradability
0	164	164	15.4	22.1	18	11.1	5.6	18.1	15.00%
0.05	156	164	24	22.9	21.4	22.8	14.1	22	8.90%
0.1	148	164	24.7	23.5	20.6	22.5	13.8	21.9	9.00%
0.15	139	164	23.3	23.8	24.5	22.1	13.6	21.8	9.10%
0.2	131	164	22.2	22.1	23.9	21.8	13.4	21.7	9.20%
0.25	123	164	22.3	24.1	23.5	21.5	13.2	21.6	9.40%
0.3	115	164	22.2	25.8	21	21.2	13	21.6	9.50%
0.35	107	164	22.1	26.5	20.3	20.9	12.8	21.5	9.10%
0.4	99	164	21.9	20.8	19.5	20.6	12.6	21.4	8.30%
0.45	91	164	21.1	23.4	20.4	20.3	12.4	21.3	7.50%
0.5	83	164	20.8	26	21.8	20	12.2	21.2	6.60%
0.55	75	164	20.7	27.9	23.2	19.7	12	21.1	5.70%
0.6	67	164	20	24.8	24.9	19.4	11.8	21	4.80%
0.65	59	164	20.9	23.6	27	19.1	11.7	21	3.80%
0.7	51	164	23.9	27.4	29.4	18.9	11.5	20.9	2.80%

TABLE 9: SERIES METHOD I PRECISION RESULTS.

| ratio HF	KW Enigne (kW)	KW Motor (kW)	m/gal MPG Cty	m/gal MPG Hwy	m/gal MPG comb	secs 0-60 (s)	secs 40-60 (s)	secs 1/4 mi (s)	percentage gradability
0.23	126	164	22.2	24.6	23.4	21.6	13.3	21.7	9.30%
0.24	125	164	22.3	24.3	23.5	21.6	13.2	21.6	9.40%
0.25	123	164	22.3	24.1	23.5	21.5	13.2	21.6	9.40%
0.26	121	164	22.3	26.2	23.1	21.4	13.2	21.6	9.40%
0.27	120	164	22.3	25.5	23.1	21.4	13.1	21.6	9.40%
0.28	118	164	22.2	26.4	23.1	21.3	13.1	21.6	9.50%
0.29	116	164	22.2	26.5	21.1	21.3	13	21.6	9.50%
0.3	115	164	22.2	25.8	21	21.2	13	21.6	9.50%
0.31	113	164	22.1	26.1	20.8	21.1	12.9	21.5	9.60%
0.32	112	164	22.2	26.1	20.7	21.1	12.9	21.5	9.60%
0.33	110	164	22.1	26.2	20.6	21.5	12.9	21.5	9.40%
0.34	109	164	22.1	26.3	20.5	21	12.8	21.5	9.35%
0.35	107	164	22.1	26.5	20.3	20.9	12.8	21.5	9.10%
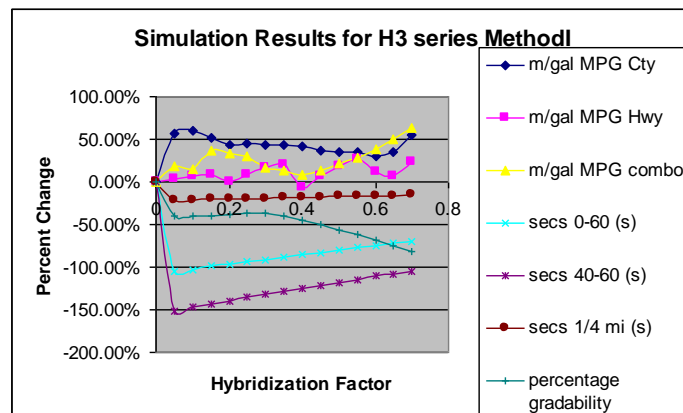
Fig. 14. H3 percent change in different parameters.

As it is clear from tables 8 and 9, the range selected for specific simulations was between HF 0.23 to HF 0.33. The best HF for this method was found at 0.28. Please see the next page for the summary of the results for H3 series method I HF of 0.28.
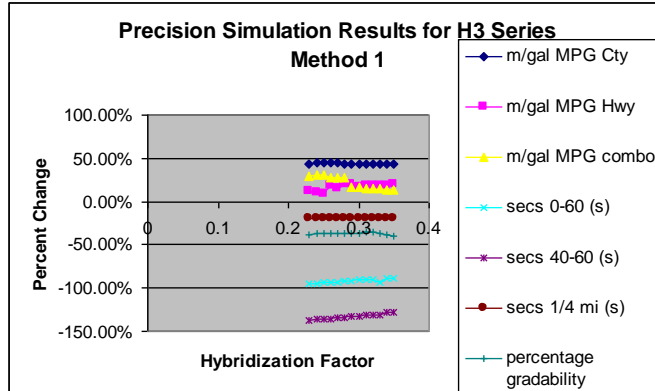
Fig 15: hummer h3 percent change precision data.

- Fuel Economy at HF = 0.28
  - ☐ City: 22.2 MPG (44.15% increase)
  - ☐ Highway: 26.4 MPG (19.45% increase)
  - ☐ Combo: 23.1 MPG (28.33% increase)
- Performance at HF = 0.28
  - ☐ 0-60: 21.3s (91.89% decrease)
  - ☐ ¼ mile: 21.6s (19.37% decrease)
  - ☐ Gradeability: 9.50% (36.67% decrease.)

The result for the series retrofit approach are present below:

TABLE 10: SERIES METHOD II SIMULATION RESULTS.

ratio HF	KW Enigne (kW)	KW Motor (kW)	m/gal MPG Cty	m/gal MPG Hwy	m/gal MPG comb	secs 0-60 (s)	secs 40-60 (s)	secs 1/4 mi (s)	percentage gradability
-0.2	164	131	22.1	22.8	20	23	14.1	22.1	8.9
-0.15	164	139	22.7	23.7	20	23.1	14.2	22.1	8.8
-0.1	164	147	22.3	21.9	19.7	23.1	14.2	22.1	8.8
-0.05	164	156	20.3	21.6	21.4	23.1	14.2	22.1	8.8
0	164	164	15.4	22.1	18	11.1	5.6	18.1	15
0.05	164	172	21	23	19.3	23.1	14.3	22.1	8.7
0.1	164	180	20.1	22.3	19.1	23.1	14.3	22.1	8.7
0.15	164	189	20	21.7	19	23.2	14.3	22.1	8.7
0.2	164	197	19.6	21	18.7	23.3	14.4	22.1	8.6

TABLE 11: SERIES METHOD II PRECISION RESULTS.

| ratio HF	KW Enigne (kW)	KW Motor (kW)	m/gal MPG Cty	m/gal MPG Hwy	m/gal MPG comb	secs 0-60 (s)	secs 40-60 (s)	secs 1/4 mi (s)	percentage gradability
-0.01	164	162	21.8	21.6	22.4	23.1	14.2	22.1	8.8
-0.02	164	161	21.3	21.6	22.5	23.1	14.2	22.1	8.8
-0.03	164	159	21.2	21.6	21.4	23.1	14.2	22.1	8.8
-0.04	164	157	21.6	21.7	22.5	23.1	14.2	22.1	8.8
-0.05	164	156	20	21.7	20.7	23.1	14.2	22.1	8.8
-0.06	164	154	21.9	21.7	20.9	23.1	14.2	22.1	8.8
-0.07	164	153	19.3	21.8	22.9	23.1	14.2	22.1	8.8
-0.08	164	151	22.1	21.8	22.8	23.1	14.2	22.1	8.8
-0.09	164	149	21.6	21.7	21.7	23.1	14.2	22.1	8.8
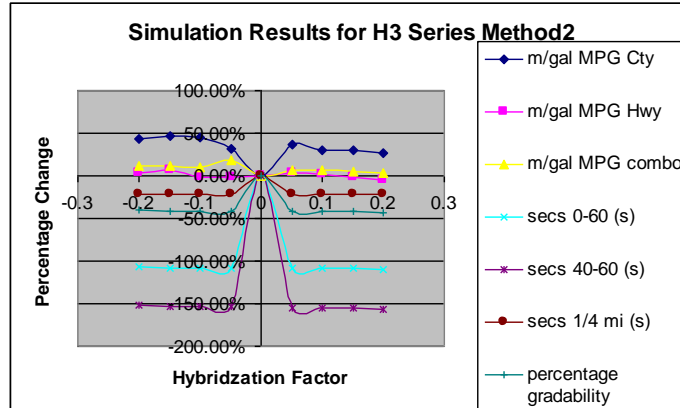
Fig. 16: H3 percent change in different parameters

Thus from the tables, one can see that the range selected was from HF of -0.10 to 0.0. The simulations seemed to have peaked at negative hybridization factors because under negative hybridizations the total power of the vehicle is less than the 164kW, thus since the fuel converter selected was ordinarily built for a power rating of 95kW, it performs better the closer it is to 95kW. The best hybridization factor was - 0.08. Please see the next page for the summary of the results at HF of -0.08.
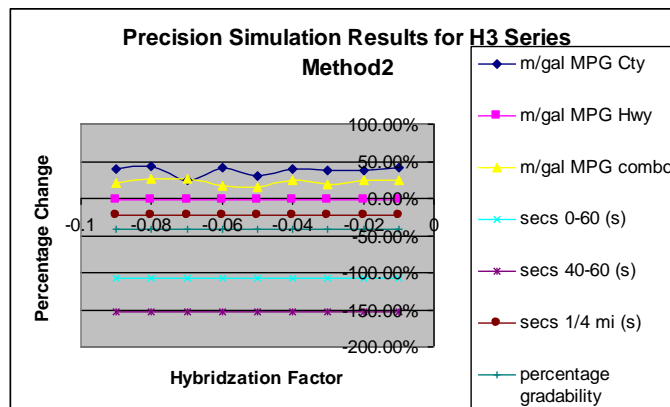
Fig 17. HUMMER h3 percent change precision data.

- ■ Fuel Economy at HF = -0.08
  - ☐ City: 22.1 MPG (43.5% increase)
  - ☐ Highway: 21.8 MPG (1.4% decrease)
  - ☐ Combo: 22.8 MPG (26.67% increase)
- ■ Performance at HF = -0.08
  - ☐ 0-60: 23.1s (108% decrease)
  - ☐ ¼ mile: 22.1 (22% decrease)
  - ☐ Gradeability: 8.80% (41.33% decrease.)

VII. CONCLUSION

The best results were obtained for Parallel method I and they were practical numbers since the hybridization factor was at 0.20. As explained earlier, the objective of this paper was focused on performance rather than fuel efficiency gains. This reaffirms our initial hypothesis of seeing performance gains as well as increases in fuel economy by hybridizing an SUV. In this paper the effects on fuel efficiency as well as performance are presented. Also it is noted here than once the Hybridization factors reach a threshold, increasing the HF does not increase the fuel efficiency significantly, but rather the performance decreases drastically. This is too large a tradeoff for nominal fuel efficiency gains.

5. Hybrid Electric Bus Simulation and Mechanical Drive Train Design:

I. Introduction

Current vehicle technology is inherently flawed in that it relies on internal combustion engines which are by nature very inefficient machines. The most efficient gasoline engine can achieve efficiencies around 35%, but average efficiencies are in the 20's . Diesel engines can achieve efficiencies of near 40%, but no internal combustion engine can exceed an efficiency of greater than 40%. Electric machines, however, can achieve near ideal efficiencies. One very successful method of improving fuel economy is to use electrical machines in the power train to supplement the internal combustion engine. This creates a hybrid electric vehicle.

A study has been undertaken to hybridize a TATA 1512 transit bus to improve its fuel economy. Because transit busses are operated under very harsh stop and go driving conditions and are very massive, their current fuel economy is very low. By retrofitting the bus with an electric machine in a parallel configuration, its fuel economy can be greatly increased. This will therefore save the operating company money as well as reduce emissions.

This paper focuses on simulations done to determine the optimum configuration for a retrofit package for the TATA 1512 transit bus. The bus was modeled in ADVISOR, the Advanced Vehicle Simulator produced by the Department of Energy. Using this program, the optimum hybridization factor was determined. Various components were also simulated to determine the best components to be used.

II. Base Model

The bus to be examined is the TATA LP 1512 medium transit bus manufactured by TATA Motors. Specifications of this bus pertinent to the simulations performed, as found on the manufacturer's website, are listed in Table 1.

Engine Specifications	
Model	TATA Cummins 6-cylinder
Displacement	5.883 L
Max Output	93.5 kW (125.3 hp) at 2500 rpm
Gear Box	
Model	GBS40, 5-Speed, Automatic
Gear Ratios	1st – 7.51 4th – 1.51 2nd – 3.99 5th – 1.00 3rd – 2.50 Reverse – 6.93
Wheelbase	5.895 m
Length	10.32 m
Width	2.434 m
Bare Chassis Curb Weight	4095 kg
Gross Vehicle Weight Rating (GVWR)	14860 kg

Table 1: Manufacturer's Advertised Specifications

Further specifications needed to complete the base model for simulations were estimated using trends from other medium transit busses. The total curb weight of the vehicle was estimated as twice the weight of the bare chassis. The fraction of the total vehicle weight on the rear drive axle was estimated to be 64%. The transmission efficiency was estimated to be 85%. The total accessory load was estimated as one 5 hp air compressor for the suspension, under the assumption that this particular bus lacks any luxury loads such as air conditioning.

The file used to model the vehicle itself was the 'RT_S06'transit bus model, based on the Nova RTS-06 40 foot Transit Bus. The model was modified to reflect the advertised and estimated specification of the TATA 1512. The engine file used was 'FC_CI119' based on a 6.54 L 8-cylinder air-cooled, naturally aspirated diesel engine. Since the main focus of this study is fuel economy, the most important factor in matching a suitable model of the engine is its displacement. The file chosen best matched the displacement of the engine used in the TATA 1512. In the simulations, this engine was scaled from 119 kW to 94 kW.

The transmission used was a modified 'Annex_VII' based on a 5-speed automatic heavy-duty transmission. This file was modified to reflect the advertised gear ratios and estimated efficiency. The standard 'ACC_HEAVY' accessory file was used, and was modified to reflect only the air compressor. The standard diesel exhaust after treatment file was used as well as the standard 'WH_HEAVY' heavy duty drive axle and standard heavy duty power train control, 'PTC_HEAVY.'

III. Test Procedure

The focus of this study is a retrofit of an existing vehicle; therefore none of the specifications of the base vehicle were changed during simulations. This also meant that a parallel hybrid configuration is to be used, simply adding an electric motor to the existing power train. This is the most cost effective method of hybridizing an existing vehicle since it does not require remanufacture of the power train.

The drive cycle used was the 'UKBUS_MASS_VAR1' drive cycle. This drive cycle is based on data gathered on a London transit bus route. This drive cycle is unique in that it takes into account the varying number of passengers through the cycle. The cargo weight is varied between 2240 kg and 3290 kg, based on 75 kg per passenger and between 32 and 47 passengers. The duration of drive cycle is 3288 seconds, or about 54 minutes and covers 7.53 miles. Its average speed is 8.25 miles per hour (mph), with a maximum speed of 26.07 mph. These factors make this drive cycle most representative of a transit bus operating in a major city of all the available drive cycles. Figure 2 shows the speed and passenger weight plotted versus time for this drive cycle.
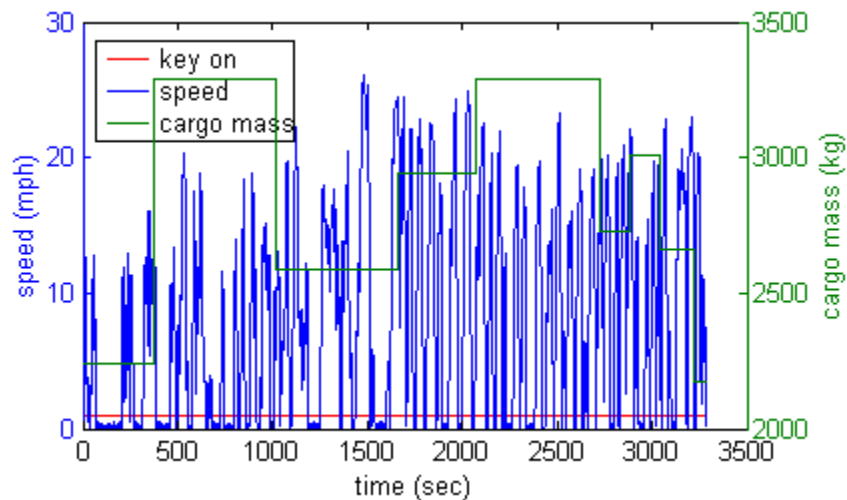
Figure 2 : Variable Mass Drive Cycle

All simulations were run using 10 drive cycles to represent a typical day's operation. Acceleration tests were performed to determine the maximum acceleration rate and maximum speed attainable. The times from 0-50 mph and from 40-50 mph were also tested.

Simulations were first run on the base model to confirm the validity of the model and as a basis for comparison of the hybrid tests. Simulations were then run for hybridization factors of between 5% and 55% to determine the optimum hybridization factor and configuration. In the hybrid tests, a balanced power train control, 'PTC_BAL' that maintained the battery charge between 50% and 70% was used. The number of battery modules used was matched to the power of the electric motor, as determined by the hybridization factor.

Initial hybrid tests were performed using a Westinghouse 75 kW AC induction motor scaled to the power of the electric motor needed for each hybridization factor tested. Three sets of simulations were run using different Nimh batteries to determine the optimum Nimh battery. The batteries used were an Ovonic 93 Ah module, 'ESS_NIMH93,' providing 1.23kW per module, Ovonic M155, 'ESS_NIMH90_OVONIC,' providing 1.1kW per module, and the General Motors EV1 GenII, 'ESS_EV1_draft,' providing 1.07kW per module. The same procedure was used to determine the optimum lead acid battery for use in hybridizing the TATA 1512. The lead acid batteries used were the GNB 12-EVB-1180 valve-regulated

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lead-acid battery, 'ESS_PB104,' providing 1.23 kW per module, the Horizon 12N85 lead-acid battery, 'ESS_PB85,' providing 1.01 kW per module, and the Horizon 12N85 lead-acid battery, 'ESS_PB91,' providing 1.05 kW per module. During tests with the lead acid batteries the GVW of the simulated vehicle was monitored to be sure it did not exceed the GVWR for the existing bus. Simulations were discontinued after this weight rating was exceeded, typically at hybridization factors of 40% or greater.

Upon completion of simulations for comparison of the various batteries, tests were performed to determine the optimum electric motor. The motors tested consisted of a prototype 62 kW, 'MC_AC62,' and 59 kW, 'MC_AC59,' AC induction motors tested by the Institute for Power Electronics and Electrical Drives at Aachen University of Technology, and a Siemens 30 kW AC induction motor. Simulations were carried out for hybridization factors of between 5% and 55% were the motor power was scaled to the needed power for each hybridization factor. The batteries used were the optimal Nimh and lead acid batteries, and the number of modules used was that needed to match the power of the motor. Again simulations were discontinued when the maximum GVWR was exceeded when using the lead acid batteries. The GVWR was not exceeded during any of the tests with the Nimh batteries.

IV. Test Results

The following tables show the results of simulations performed to compare the Nimh batteries. Additionally, the fuel economy and acceleration rate are plotted versus hybridization factor. In determining the optimum battery, the main factor of consideration was the fuel economy.

HF (%)	Motor Power (kW)	Modules Used	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s^2)	max speed (mph)	trace miss (mph)
0	0.00	0.0		4.9	63.8	29.7	6.4	55.7	2.25
5	4.95	10.0	12412	5.1	53.2	23.6	7.3	56.1	4.8
10	10.44	10.0	12419	5.4	44.1	19	8.8	58.9	2.6
15	16.59	16.0	12497	5.6	37.5	15.6	11.7	62.1	2.1
20	23.50	22.0	12597	5.8	32.3	13.1	11.9	65.4	0
25	31.33	30.0	12677	6.1	28.1	11.1	13.4	68.8	0
30	40.29	38.0	12781	6.1	24.6	9.5	17.1	72.2	0
35	50.62	48.0	12909	6.2	21.8	8.3	18.3	75.5	0
40	62.67	59.0	13051	6.3	19.2	7.1	18.3	79.1	0
45	76.91	72.0	13219	6.3	17	6.2	18.3	79.4	0
50	94.00	88.0	13426	6.3	15	5.4	18.3	79.4	0
55	114.89	108.0	13683	6.4	13.2	4.7	18.3	79.3	0

Table 2 : General Motors EV1 GenII Battery Test Results
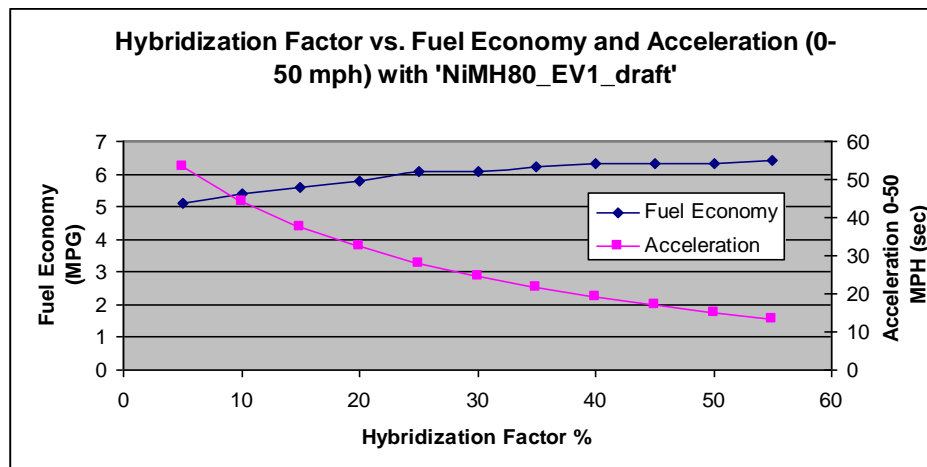
HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	trace miss (mph)
0	0	0		0	0				
5	5	10		5.1	53.7	23.8	7.2	56.1	
10	11	10		5.2	43.9	18.8	8.8	59.1	
15	17	14		5.4	37.7	15.7	12.8	62	
20	24	20		5.6	35.6	14.7	13.2	63.3	
25	32	26		5.9	28.4	11.3	14	68.6	
30	41	33		6.1	24.9	9.7	16.9	71.9	
32	45	36		6.1	23.6	9.2	18.3	73.3	
35	51	42		6.1	22.1	8.5	18.3	75.2	
40	63	51		6.2	19.6	7.3	18.3	78.8	
45	77	63		6.2	17.4	6.4	18.3	79.4	
50	94	77		6.3	15.5	5.6	18.3	79.4	
55	115	94		6.4	13.7	4.9	18.3	79.3	

Table 3: Ovonic 93Ah Battery Test Results
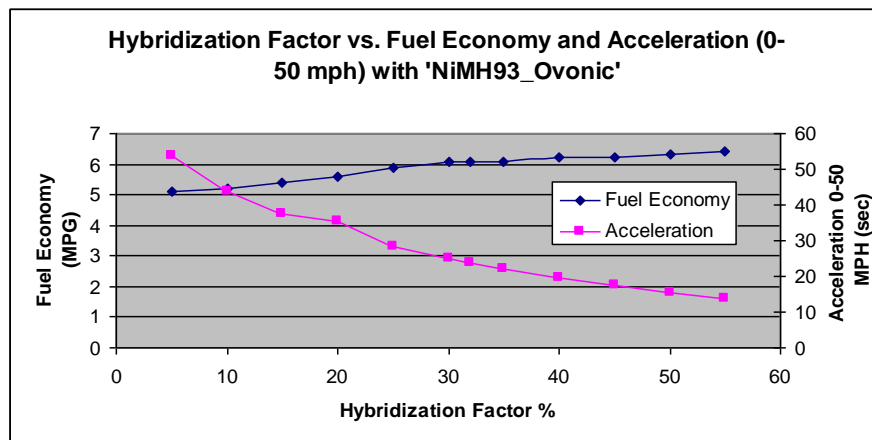
Hybridization Factor vs. Fuel Economy and Acceleration (0-50 mph) with 'NiMH93_Ovonic'

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	trace miss (mph)
5	5	10	12463	5	59.6	25.5	7.2	56.1	
10	10	10	12469	5.4	45.4	19.2	8.6	59	
15	17	15	12562	5.6	39.1	16	10.5	61.8	
20	24	21	12670	5.9	33.9	13.5	10.2	65	
25	31	28	12796	6.1	30.1	11.8	12.8	68	
30	40	37	12957	6.2	26.3	10.1	16.4	71.4	
35	51	46	13120	6.1	22.8	6.8	18.3	75.1	
40	63	57	13319	6.2	20.1	7.5	18.3	78.7	
45	77	70	13661	6.3	17.8	6.5	18.3	79.4	
50	94	85	13825	6.3	15.8	5.7	18.3	79.4	
55	115	104	14167	6.3	14	4.9	18.3	79.3	

Table 4 : Ovonic M155 Battery Test Results
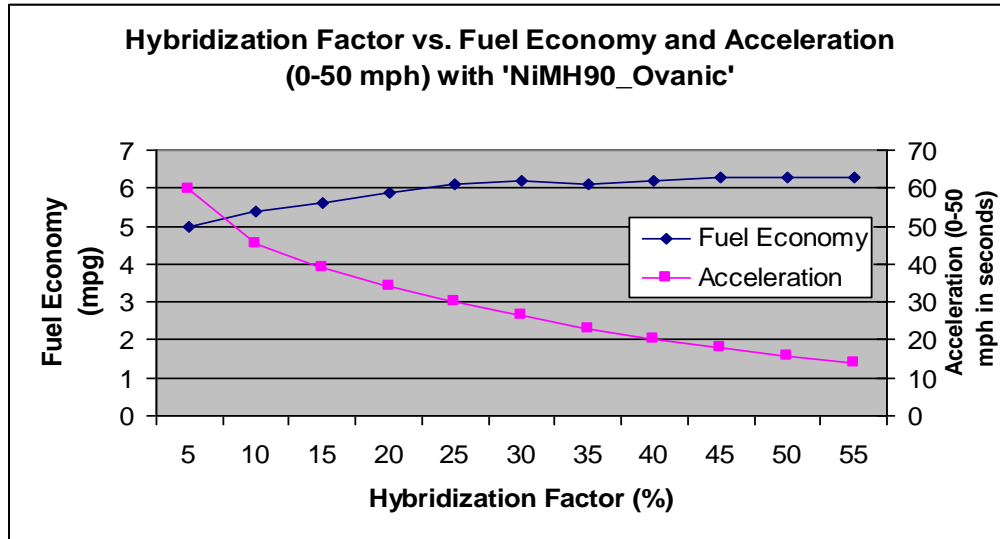
Of the Nimh batteries, the Ovonic M155, 'ESS_NIMH90_OVONIC,' is the optimum battery for application in the hybrid bus. This battery was able to achieve the greatest fuel economy at the lowest hybridization factor, 6.1 mpg at 25% hybridization. The following tables show the results of the comparison of the lead acid batteries. Additionally, the fuel economy and acceleration rate are plotted versus hybridization factor

HF	Motor Power	Modules Used	GVW (50 pass)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s^2)	max speed (mph)	trace miss (mph)
0	0.00	0		4.9	63.8	29.7	6.4	55.7	2.25
5	4.95	10	12545	6.3	57.5	25.4	7.1	56.1	3.9
10	10.44	11	12577	5.4	46.4	19.5	9.7	58.8	3.8
15	16.59	17	12742	5.4	39.9	16.1	8.1	61.7	2.2
20	23.50	24	12917	5.5	34.6	13.7	9.7	64.7	0
25	31.33	31	13101	5.6	30	11.8	12.8	68.1	0
30	40.29	40	13336	5.6	26.5	10.2	16.2	71.3	0
35	50.62	51	13622	5.6	23.6	9	18.3	74.5	0
40	62.67	62	13911	5.6	21	7.9	18.3	78	0
45	76.91	77	14301	5.6	18.9	7	18.3	79.5	0
50	94.00	94	14746	5.5	17	6.2	18.3	79.4	0

Table 5 : Horizon 12N85 Lead-acid Battery Test Results
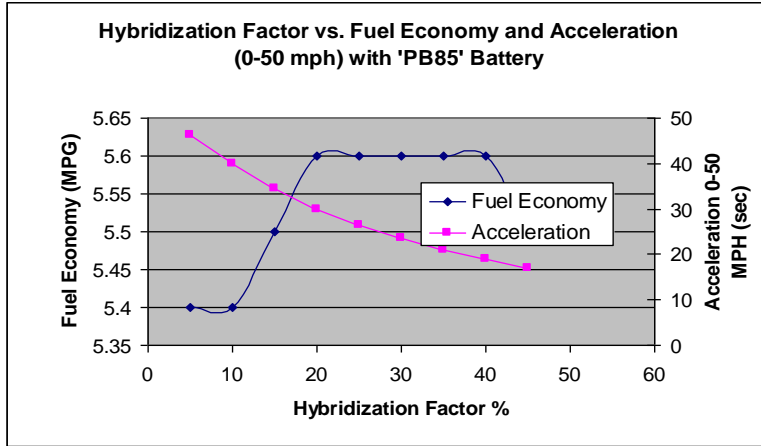
Hybridization Factor vs. Fuel Economy and Acceleration (0-50 mph) with 'PB85' Battery

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s^2)	max speed (mph)	trace miss (mph)
5	5	10		5.9	54.6	24.4	7.1	56.1	
10	11	10		6.5	54.4	24.5	8.6	56.1	
15	17	13		5.2	38.5	16	11.5	61.8	
20	24	19		5.5	33.7	13.7	11.1	64.8	
25	32	25		5.5	29.5	11.7	12.9	68.1	
30	41	32		5.6	26.1	10.2	16.2	71.4	
35	51	40		5.6	23.5	8.9	18.3	74.6	
40	63	49		5.6	20.9	7.8	18.3	78.1	
43	71	56		5.6	19.6	7.3	18.3	79.5	
44	74	58		5.6	19.1	7.1	18.3	79.5	
45	77	61		5.6	18.7	6.9	18.3	79.5	
46	81	63		5.5	18.2	6.7	18.3	79.5	
50	94	74		5.4	16.8	6.1	18.3	79.4	
55	115	90		5.3	15	5.4	18.3	79.4	

Table 6 : GNB 12-EVB-1180 Battery Test Results
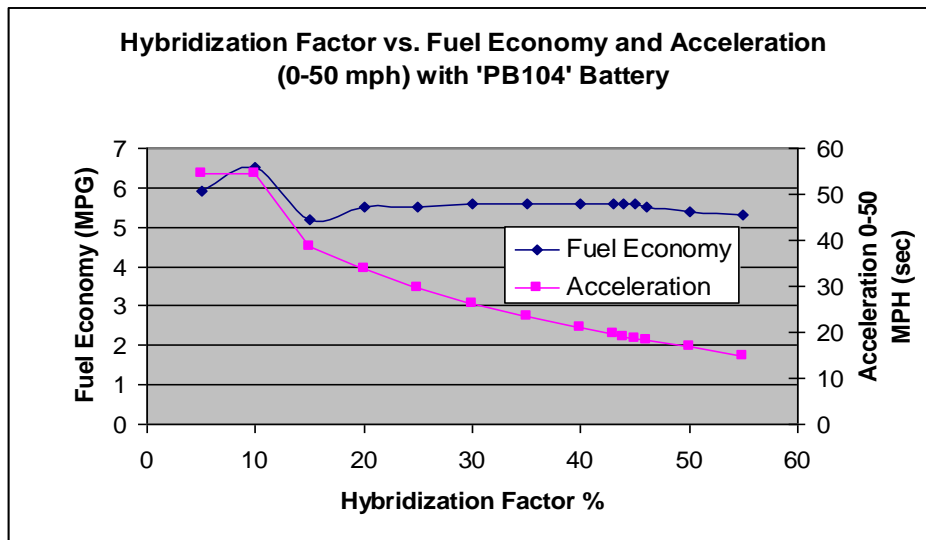
Hybridization Factor vs. Fuel Economy and Acceleration (0-50 mph) with 'PB104' Battery

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s^2)	max speed (mph)
5	5	5	12555	4.9	57.7	25.2	7.1	56.2
10	10	10	12551	5.2	46.6	19.5	9	58.7
15	17	16	12709	5.5	41.5	16.4	7.7	61.4
20	24	22	12867	5.6	35.5	13.9	9.7	64.4
25	31	30	13075	5.7	31.3	12.2	12.5	67.5
30	40	38	13285	5.7	27.3	10.5	15.8	10.9
35	51	48	13547	5.7	24	9.1	18.3	74.5
40	63	60	13861	5.7	21.3	8	18.3	78

Table 7 : Horizon 12N85 Battery Test Results

Title: Hybridization Factor vs. Fuel Economy and Acceleration (0-50 mph) with 'PB91' Battery

Of the lead acid batteries, the Horizon 12N85, 'ESS_PB91,' is the optimum battery for application in the hybrid bus. This battery was able to achieve the greatest fuel economy at the lowest hybridization factor, 5.7 mpg at 25% hybridization.

The following tables show the results of the comparison tests for the motors.
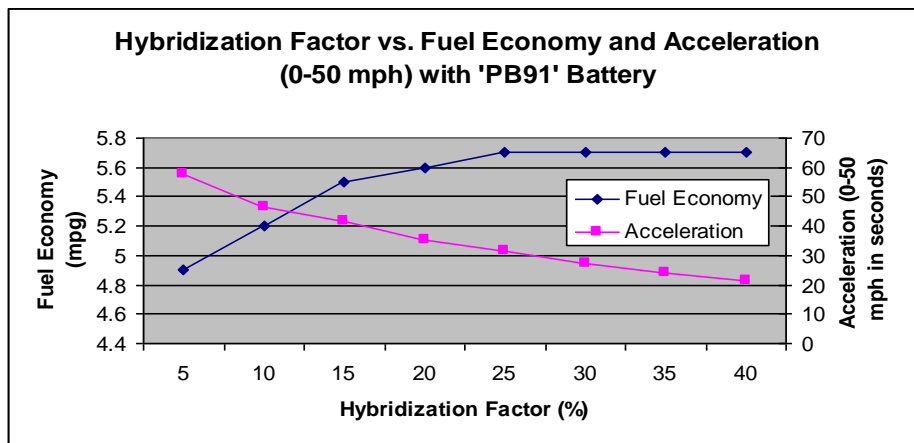
HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s^2)	max speed (mph)	trace miss (mph)
0		0	3500						
5	5	10	12463	5.3	59.9	26.5	6.1	56.1	6.8
10	11	10	12469	5.1	52	22.8	7.3	56.1	5.3
15	17	16	12576	5.2	48.4	20.4	7.9	58.1	6.6
20	24	22	12684	5.4	43.9	18.1	8.3	59.8	3.7
25	32	29	12810	5.5	40	16.1	8.2	61.7	2.6
30	41	37	12954	5.6	36.6	14.4	8	63.9	0
35	51	47	13132	5.7	33.1	12.9	8.6	66.1	0
40	63	57	13313	5.7	29.8	11.6	9.5	68.7	0
45	77	70	13546	5.7	26.9	10.3	11.4	71.3	0
50	94	86	13832	5.6	24.3	9.2	13.7	74.1	0

Table 8 : AC 62 Results using Ovonic M155

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	trace miss (mph)
0		0	3500						
5	5	10	12545	5.1	60.6	26.9	6.7	56.1	8.1
10	11	10	12551	5	52.7	23.1	7.2	56.1	5.7
15	17	16	12707	4.9	53	20.8	6.7	57.8	6.5
20	24	23	12890	5.1	47.1	18.7	6.9	59.4	3.8
25	32	30	13083	5.3	42.2	16.7	7.3	61.3	2.7
30	41	39	13307	5.3	38.2	15.1	7.8	63.3	0
35	51	49	13567	5.3	34.8	13.7	8.3	65.4	0
40	63	60	13855	5.2	31.7	12.4	9	67.8	0

Table 9 : AC 62 Test Results using Horizon 12N85 Battery

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	Make Cycle
0	0	0		4.9	63.9	29.7	6.4	55.7	YES
5	5	10		5.1	61.3	27.5	6.7	56.1	NO
10	11	10		5	54.8	24.6	7.2	56.1	NO
15	17	16		5.2	51.8	22.6	8	57.1	NO
20	24	22		5.4	47.9	20.6	8.2	58.2	NO
25	32	29		5.6	44.5	18.7	7.7	59.5	NO
30	41	37		5.8	41.4	17.1	7.3	61	NO
35	51	47		5.9	38.1	15.6	7.9	62.7	YES
40	63	57		6.1	34.8	14.2	9.7	64.5	YES
45	77	70		6.2	31.9	12.9	11.7	66.4	YES
50	94	86		6.3	29.1	11.7	13.9	68.5	YES

Table 10 : AC 59 Test Results Using Ovonic M155

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	Make Cycle
0	0	0		4.9	63.9	29.7	6.4	55.7	YES
5	5	10		4.8	62.1	27.9	6.6	56.1	NO
10	11	10		4.8	55.5	24.9	7.2	56.1	NO
15	17	16		4.9	57	23	6.4	56.1	NO
20	24	23		5.1	51.7	21.2	6.5	57.8	NO
25	32	30		5.2	47	19.5	6.7	59.1	NO
30	41	39		5.4	43.3	18	7	60.5	NO
35	51	49		5.5	40.1	16.6	7.6	62	YES
40	63	60		5.6	37.1	15.2	9.2	63.7	YES
45	77	74		5.6	34.4	14	10.9	65.5	YES
50	94	90		5.6	31.8	12.8	12.9	67.4	YES

Table 11: AC 59 Results Using Horizon 12N85 Battery

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	% Missed
0	0	0		4.9	63.9	29.7	6.4	55.7	
5	5	10	12467	2.5					54%
10	11	10	12477	2.6					53%
15	17	16	12575	4	49	28.2	18.3	58.1	0.94%
20	24	23	12689	4.2	45.2	18.9	18.3	59.7	0.61%
25	32	30	12703	4.4	42.5	17.1	18.3	61.2	0.29%
30	41	39	12987	4.4	33.9	16.3	18.3	63.2	0.14%
35	51	49	13159	4.4	35.2	13.6	18.3	65.6	0.02%
40	63	60	13367	4.4	31.7	12.2	18.3	68	0%
45	77	74	13612	4.5	28.5	10.9	18.3	70.5	0%
50	94	90	13897	4.6	25.7	9.7	18.3	73.3	0%
55	115	110	14255	4.7	23.1	8.8	18.3	76.4	0%

Table 12 : AC 30 Results Using Ovonic M155 Battery

HF	Motor Power	Battery Modules	GVW (kg)	mpg	0-50 Time (s)	40-50 Time (s)	max acceleration (ft/s²)	max speed (mph)	% Missed
0	0	0		4.9	63.9	29.7	6.4	55.7	
5	5	10	12425	6.9			70.9	23.1	23.19%
10	11	10	12559	6.9			72	23.2	23.18%
15	17	16	12722	6.9			782	23.2	23.18%
20	24	23	12886	4	50.4	19.5	18.3	59.1	0.56%
25	32	30	13099	4.1	45.7	17.8	18.3	60.7	0.29%
30	41	39	13315	4.1	41	16	18.3	62.7	0.21%
35	51	49	13586	4.2	36.9	14.4	18.3	64.9	0.02%
40	63	60	13909	5	32.3	13	18.3	67.3	0.00%
45	77	74	14261	4.9	29.5	11.8	18.3	69.7	0.00%
50	94	90	14718	4.7	27.2	10.6	18.3	72.2	0.00%
55	115	110	15232	4.5	24.8	9.6	18.3	75.1	0.00%

Table 13: AC 30 Results Using Horizon 12N85 Battery

V. Recommendations

The recommended battery for use in this application is the Ovonic M155, 'ESS_NIMH90_OVONIC.' Use of this battery will give the lowest fuel consumption for a given hybridization factor. If it is not cost effective to use this battery, the Horizon 12N85 lead acid battery, 'ESS_PB91,' is recommended. The recommended motor to be used is the Westinghouse 75 kW AC induction motor scaled to the needed power. This motor provided the lowest fuel consumption for all of the motors tested.
The recommended hybridization factor is 25%. At this hybridization a 32 kW electric motor is used. It is recommended that the appropriate number of battery modules be used to match the motor power.

VI. Conclusion

Through hybridizing the TATA 1512, a significant increase in fuel economy can be achieved. Using the recommended optimum configuration, a fuel economy of 6.1 miles per gallon can be achieved. This is a 25% increase in the 4.9 miles per gallon of the conventional bus. Performance is also increased; with a 53% increase in acceleration and 23% increase in maximum speed.

<u>Acknowledgments</u>